Deformation Analysis with Point Clouds

Advanced Techniques for Mobile Sensing and Robotics (Geodesy Track)

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SS 2020

Agenda

7 Deformation analysis with point clouds

Learning objectives

- What is a deformation analysis?
- How to perform a deformation analysis with point clouds?
- What are the challenges?

7 Deformation analysis with point clouds

7.1 Aim of deformation analyses

Aim of deformation analyses

Determine geometric changes of objects related to a reference epoch

- **Structural objects**: buildings, bridges, dams, tunnels, crane rails, ...
- **Industrial objects**: turbines, ships, radio telescopes, ...
- **Environmental objects**: subsidence of ground, mining damages, sliding slopes, tectonic movements, ...

- **Damage prevention**: detecting even small changes in time
- **Conservation of evidence**: identifying acting forces
- **Forecasting of performance**: parameterizing geometric behavior under certain conditions
- **Verifying construction/material properties**: multidisciplinarity with civil engineers, geologists or others

- *Also: deformation measurements, monitoring, change detection*

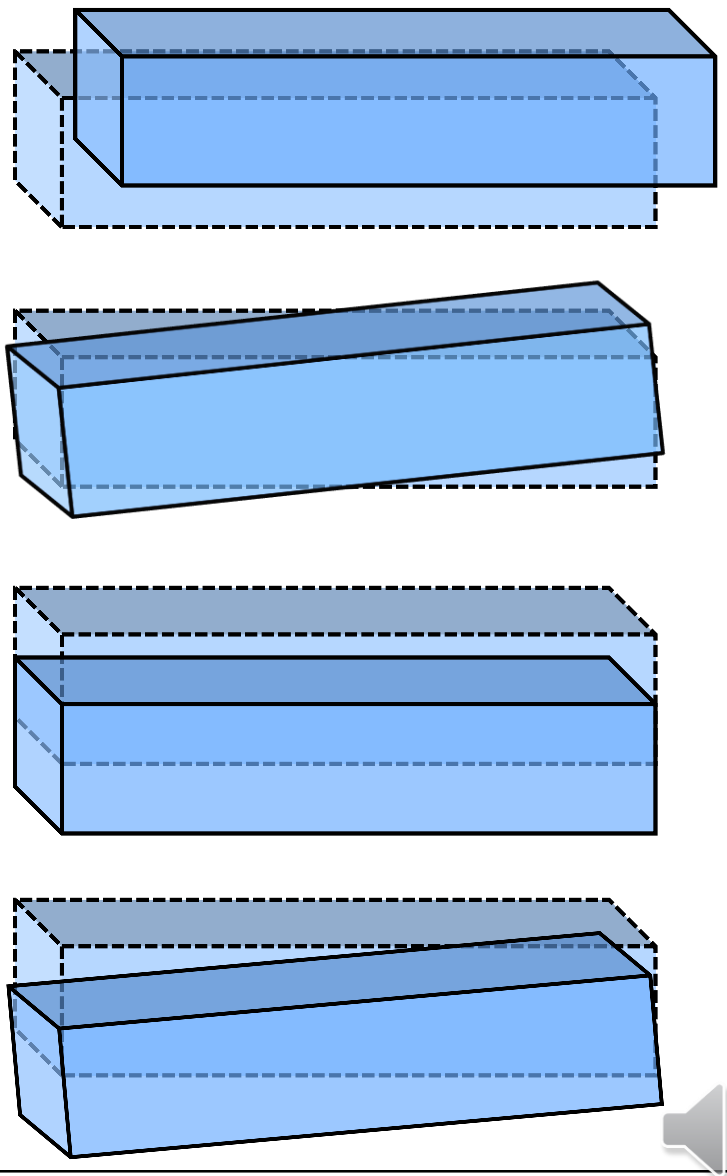
Changes A) Rigid body movement

- **structures moves as a whole**

- Translation (X, Y, Z)
- Rotation (α, β, γ)

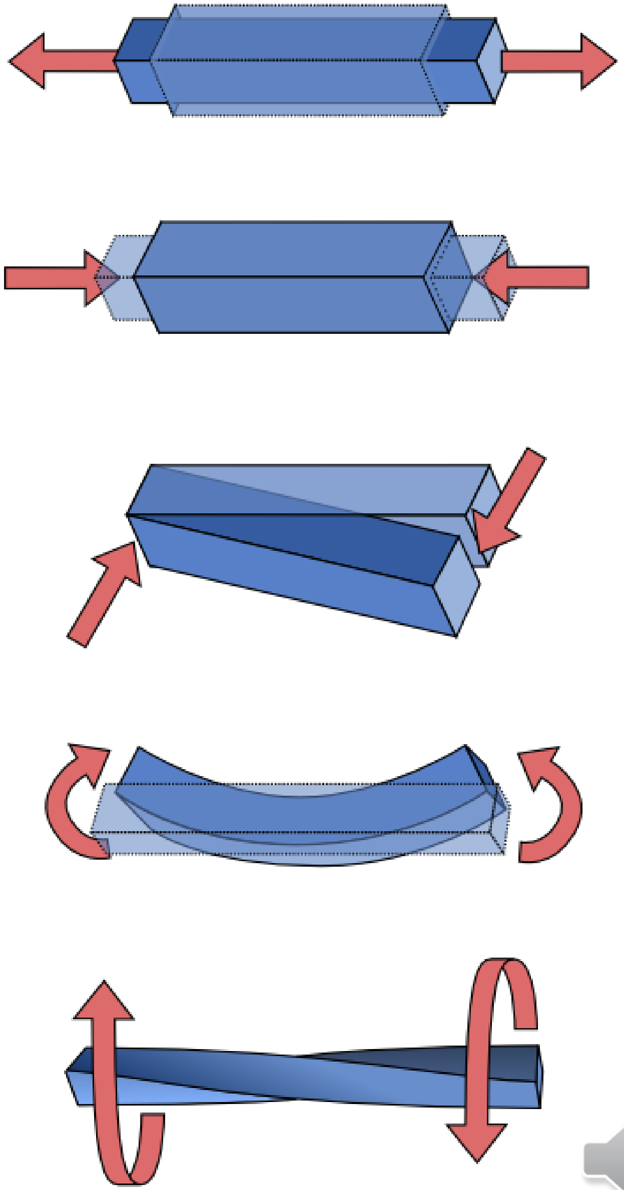
- Subsidence (Z) due to removal of mass in underground
- Settlement (Z) due to changes in load

- Tilt due to uneven subsidence/settlement



Changes B) Shape deformations

- **change of structure‘s inner geometry**
- Expansion and compression: relative changes in length
- Shear: relative displacement along a material cross section
- Deflection rectangular to an axis
- Torsion around an axis



Example: Monitoring of water dam

- Material: rubblestone
- Length of Crown: 200 m
- Height: 25 m
- Width at bottom: 17 m
- Width at top: 4.5 m

- **How does it deform?**

=> Rigid body movement vs. shape deformation, quantity, spatial variation, direction

- **What are the acting forces?**

=> Temperature (air, water), water level

7 Deformation analysis with point clouds

7.2 Deformation models

Deformation models

	Congruence model	Kinematic model	Static model	Dynamic model
Time	**No**	**Function of time**	**No**	**Function of time and loads**
Acting forces	**No**	**No**	**Function of loads**	
State of the object	Sufficiently in equilibrium	Permanently in motion	Sufficiently in equilibrium under loads	Permanently in motion
Forecast possible?	No	Yes, if forces act consistently	Yes	Yes

Congruence model

- Describes a purely geometrical comparison between the current state x_t and the previous one x_{t-1} of an object without explicitly regarding "time" and "loads“

$$\boldsymbol{x}_t = \boldsymbol{x}_{t-1} + \boldsymbol{v}$$

- The first step of analysis is to examine the geometrical identity of an object on the basis of statistical tests

$$\boldsymbol{d} = \boldsymbol{x}_t - \boldsymbol{x}_{t-1}; \qquad \boldsymbol{\Sigma}_{dd} = \boldsymbol{\Sigma}_{xx,t} + \boldsymbol{\Sigma}_{xx,t-1}$$

$$T_d = \frac{\boldsymbol{d}^T \boldsymbol{\Sigma}_{dd}^{-1} \boldsymbol{d}}{\mathrm{rank}(\boldsymbol{\Sigma}_{dd})} \geq F_{\mathrm{rank}(\boldsymbol{\Sigma}_{dd}),r,1-\alpha}$$

- **To determine: Has object moved? => Yes or no!**

Kinematic model

- Describes geometric changes between the current state x_t and previous one(s) with time lag τ by time functions φ without regarding potential relationships to causative forces

$$\boldsymbol{x}_t = \varphi(\boldsymbol{x}_{t-\tau}) + \boldsymbol{v}$$

- Polynomial approaches, especially velocities and accelerations, and harmonic functions are commonly applied

$$\boldsymbol{x}_t = \boldsymbol{x}_{t-\tau} + \underbrace{\frac{\partial x}{\partial t}(\boldsymbol{x}_t - \boldsymbol{x}_{t-\tau})}_{\dot{x}\cdot\Delta t} + \frac{1}{2}\underbrace{\frac{\partial^2 x}{\partial t^2}(\boldsymbol{x}_t - \boldsymbol{x}_{t-\tau})^2}_{\ddot{x}\cdot\Delta t^2} + \cdots$$

- **To determine: Parameters of function φ (here: $\dot{x}, \ddot{x}$)**

Static model

- Describes the functional relationship φ between loads as causative forces f_t and geometrical reactions of an object x_t without regarding time aspects

$$\boldsymbol{x}_t = \varphi(\boldsymbol{f}_t) + \boldsymbol{v}$$

- The object has to be sufficiently in a state of equilibrium during the observation epochs
- The behavior between the epochs remains unknown and is not of interest in a static model

$$\boldsymbol{x}_t = \alpha_T \cdot L \cdot \Delta T$$

(α_T: expansion coefficient, L: length, ΔT: temperature change)

- **To determine: Parameters of function φ (here: α_T)**

Dynamic model

- Describes the behavior of an object with respect to previous states $x_{t-\tau}$ with time lag τ and forces f_t

$$\boldsymbol{x}_t = \varphi(\boldsymbol{x}_{t-\tau}, \boldsymbol{f}_t) + \boldsymbol{v}$$

- A dynamic model integrates the capabilities of static and kinematic models

- **To determine: Parameters of function φ**

Input signal: causative forces $\boldsymbol{f}_t$ → Transmission through the object φ → Output signal: deformation $\boldsymbol{x}_t$

Interim summary

$$x_t = \varphi(x_{t-\tau}, f_t) + v$$

Model selection determines input of φ

Model selection based on objectives of analysis

=> Interest in forecasting, ability to measure forces, complexity of system

Not yet answered:

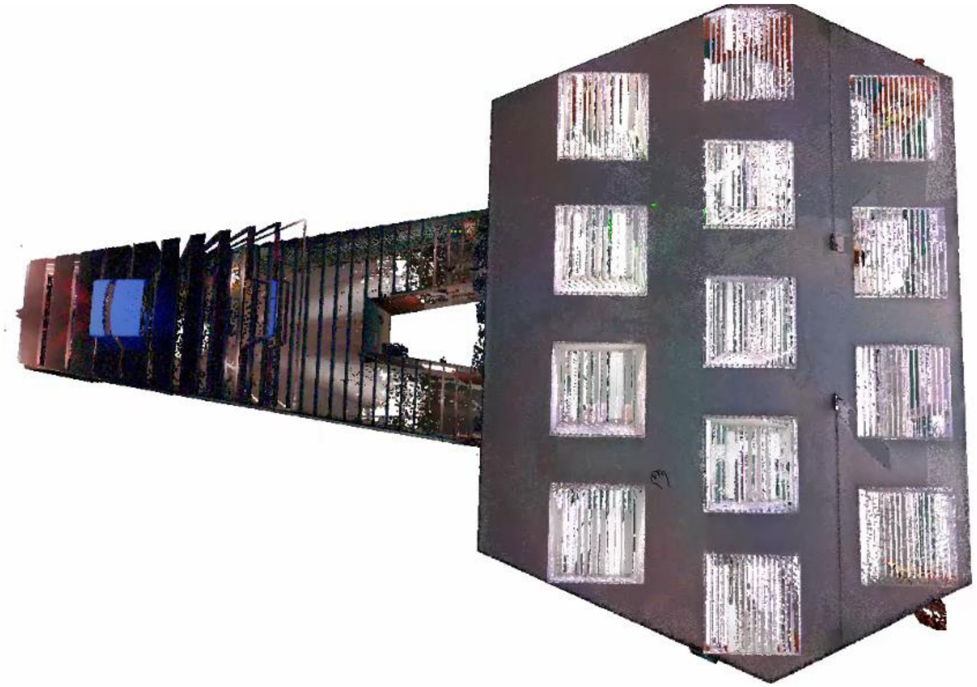
What is x_t?

7 Deformation analysis with point clouds

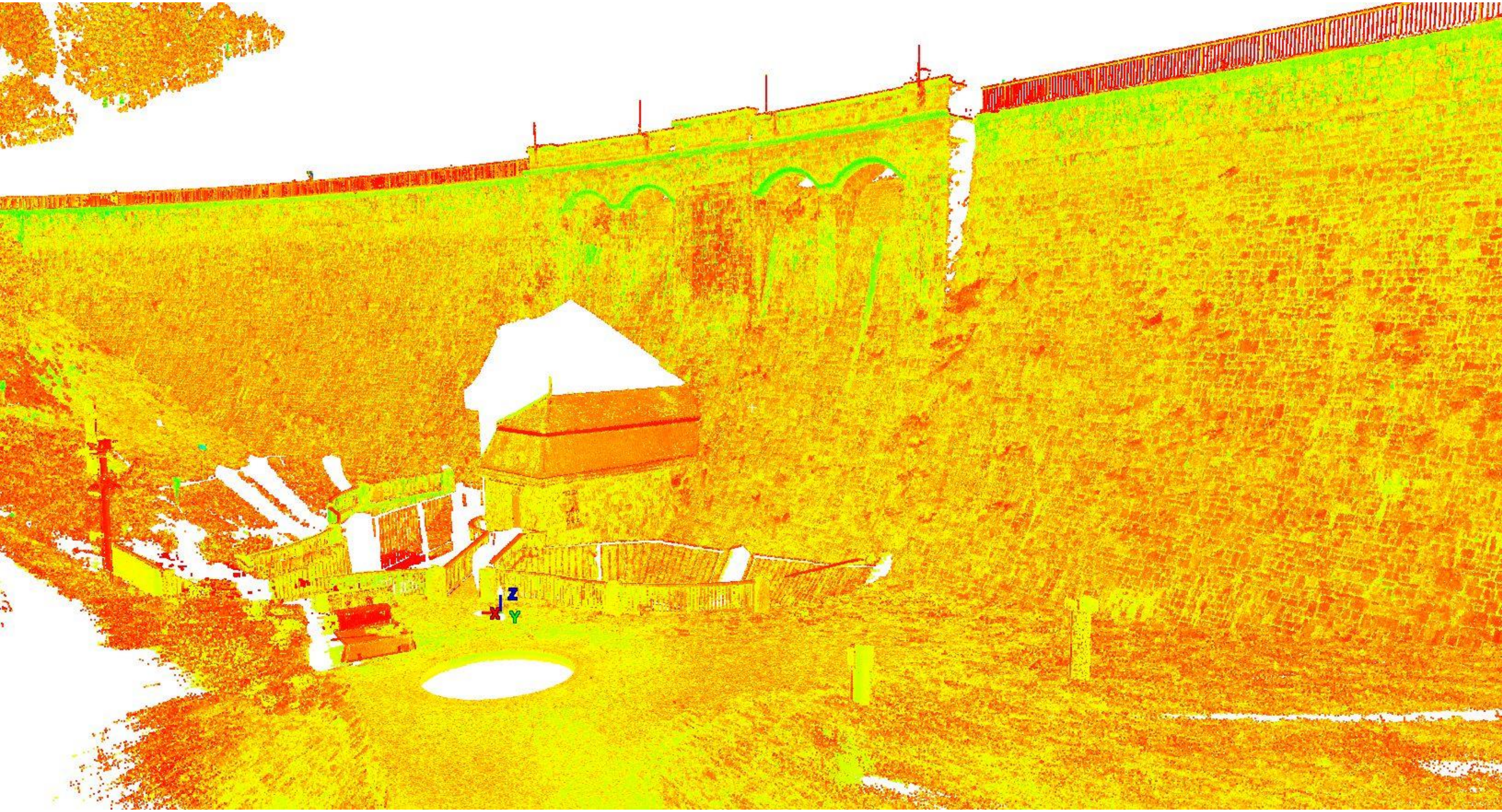
Characteristics of point cloud

- Fully automatic data acquisition
- Million of points, **no pre-selection, no semantic information**
- **3D/4D/7D point cloud** (X,Y,Z,I,R,G,B)

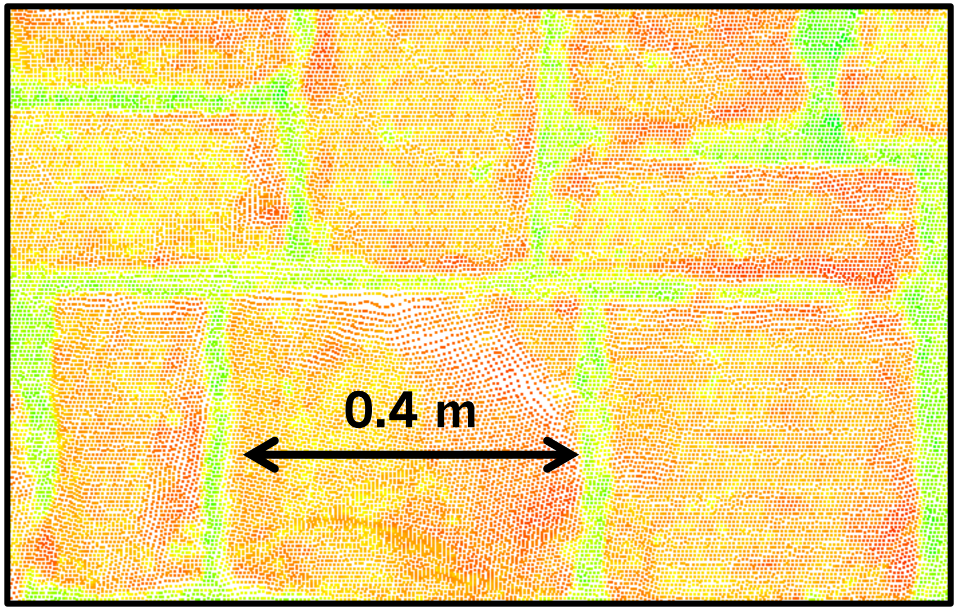
=> Redundancy beats accuracy

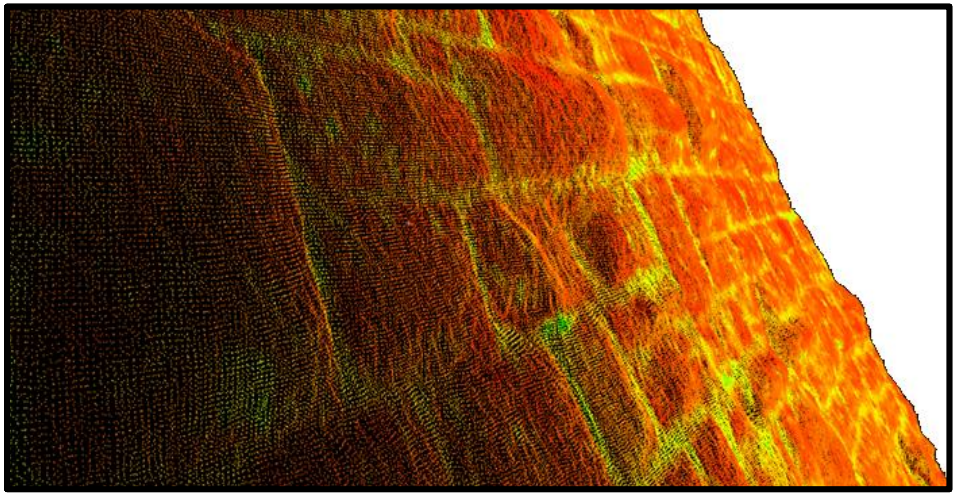


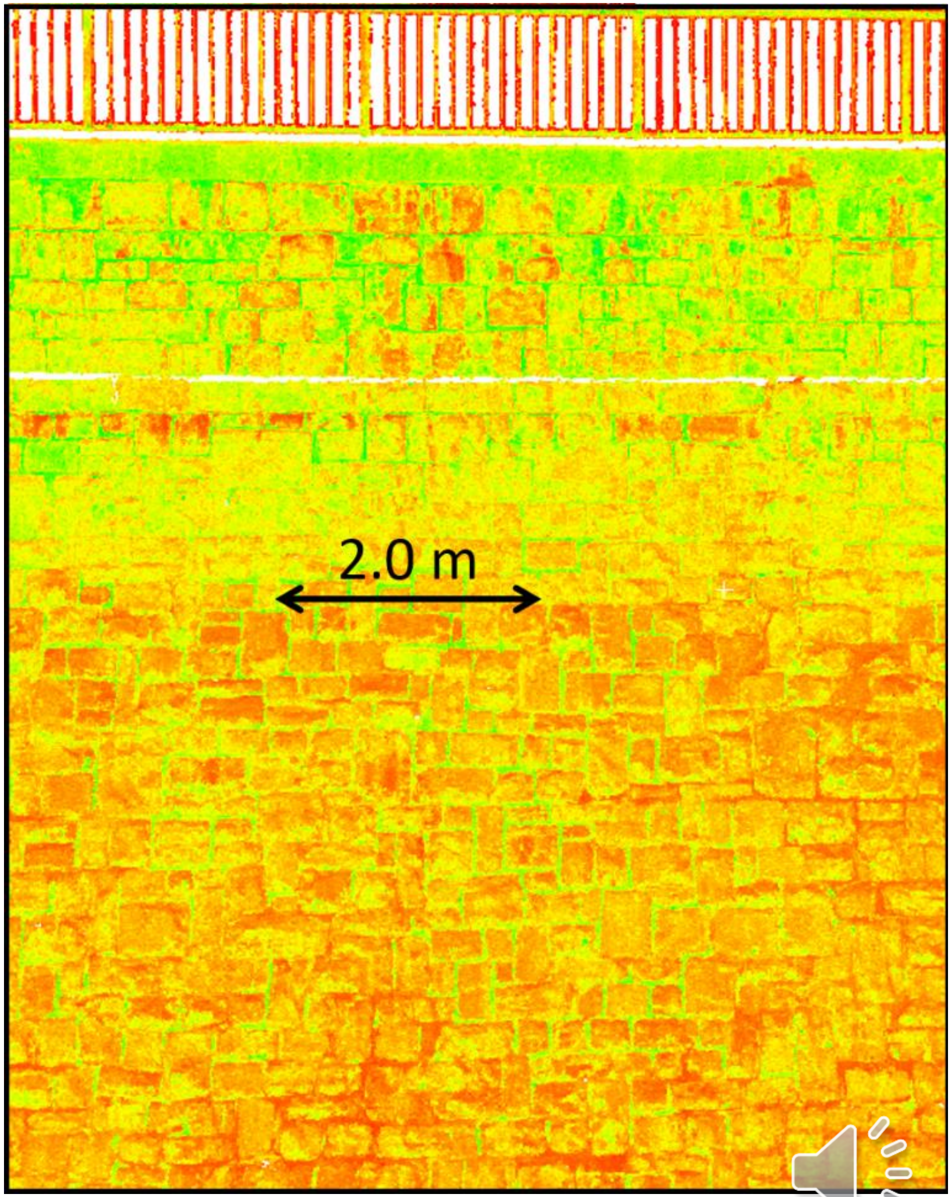
Point cloud of dam



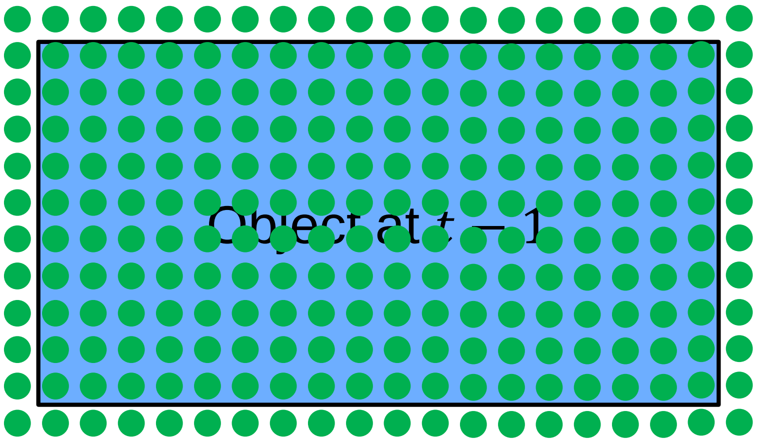
Detail view

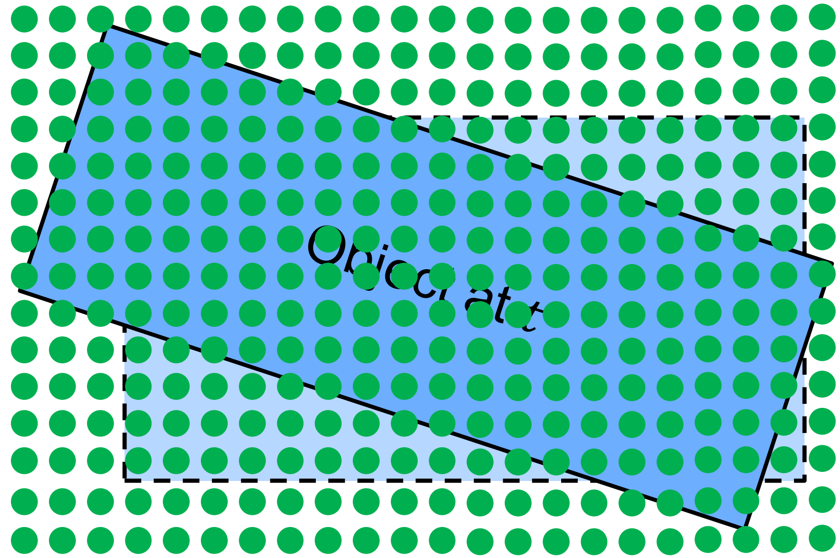






Point cloud and deformations





- Given: Two point clouds without any point-wise connection
- Assumption: Stable geo-referencing

- **How to reveal geometric changes?**
- **What to compare**
- **What is $\boldsymbol{x}_t \Rightarrow \boldsymbol{d} \Rightarrow T_d$?**

- *From now on: Limited to congruence model, but expandable*

7 Deformation analysis with point clouds

7.3 Approaches for revealing changes in point clouds

7.3.1 Problem statement

7.3.2 Introducing the approaches

7.3.3 Open challenges

Wat is not addressed!

Different concepts for structuring

- Lindenbergh & Pietrzyk (2015), Mukupa et al. (2016), Holst & Kuhlmann (2016), Neuner et al. (2016), Wunderlich et al. (2016), Wujanz (2016,2019)

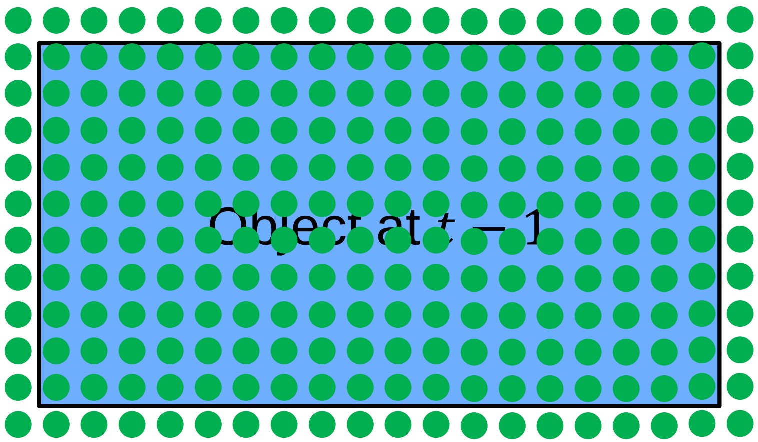
=> Here: surface based, point based, parameter based

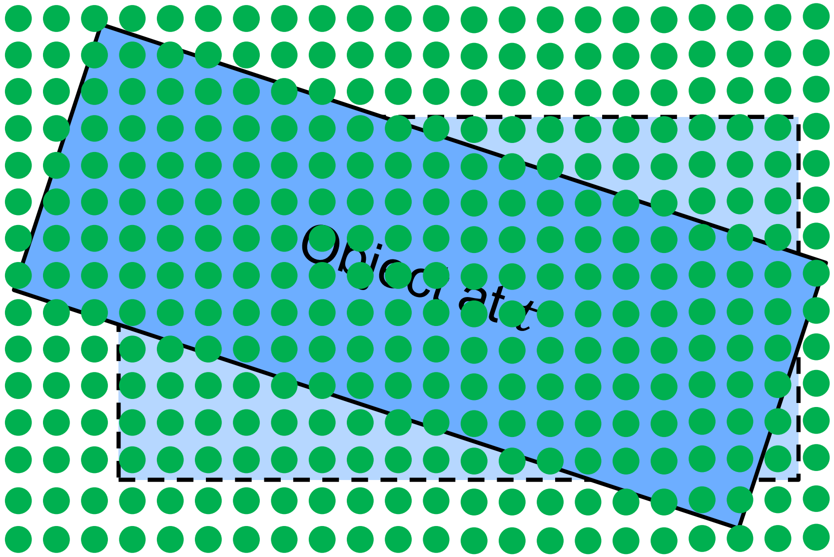
Detailed comparison of approaches

- **Outcomes:** color-coded inspection map (1D), vector differences (2D/3D), parameter differences
- **Level of detail:** complete point cloud vs. spatial generalization
- **Use cases:** In-plane vs. out-of-plane deformation, infrastructure vs. environmental
- **Complexity:** Free 1-click-software (M3C2) vs. up-to-date prototype research (Gojcic et al. 2020, Wunderlich et al. 2020)

- **But: Idea of each approach with methodological differences**

A) Surface based approach

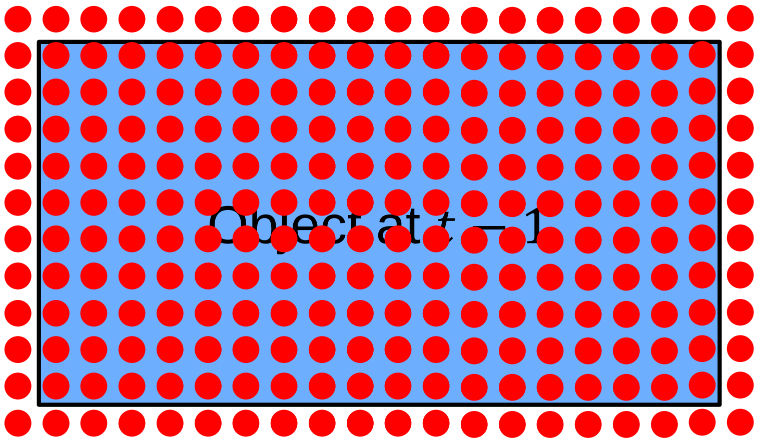


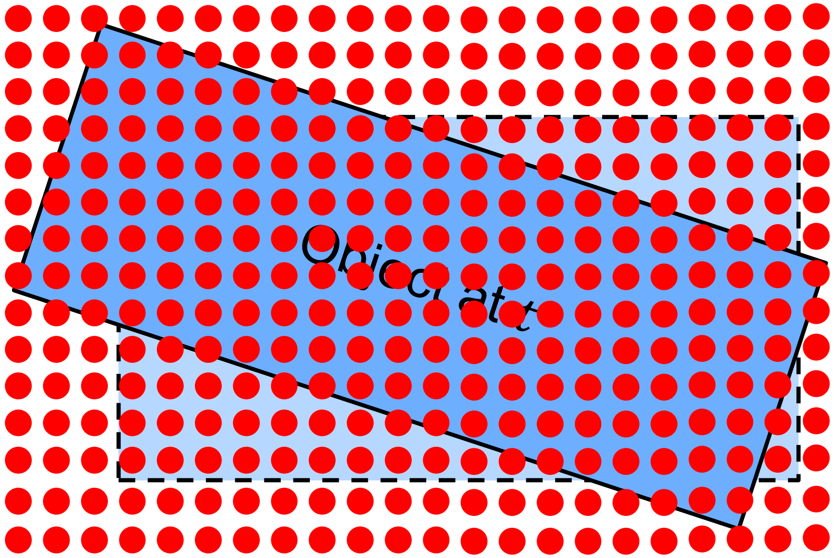


Characteristics of approach:

- Point cloud is taken as a whole
- No semantic information is given to the individual points
- Geometric changes for (nearly) each point of point cloud

A) Surface based approach



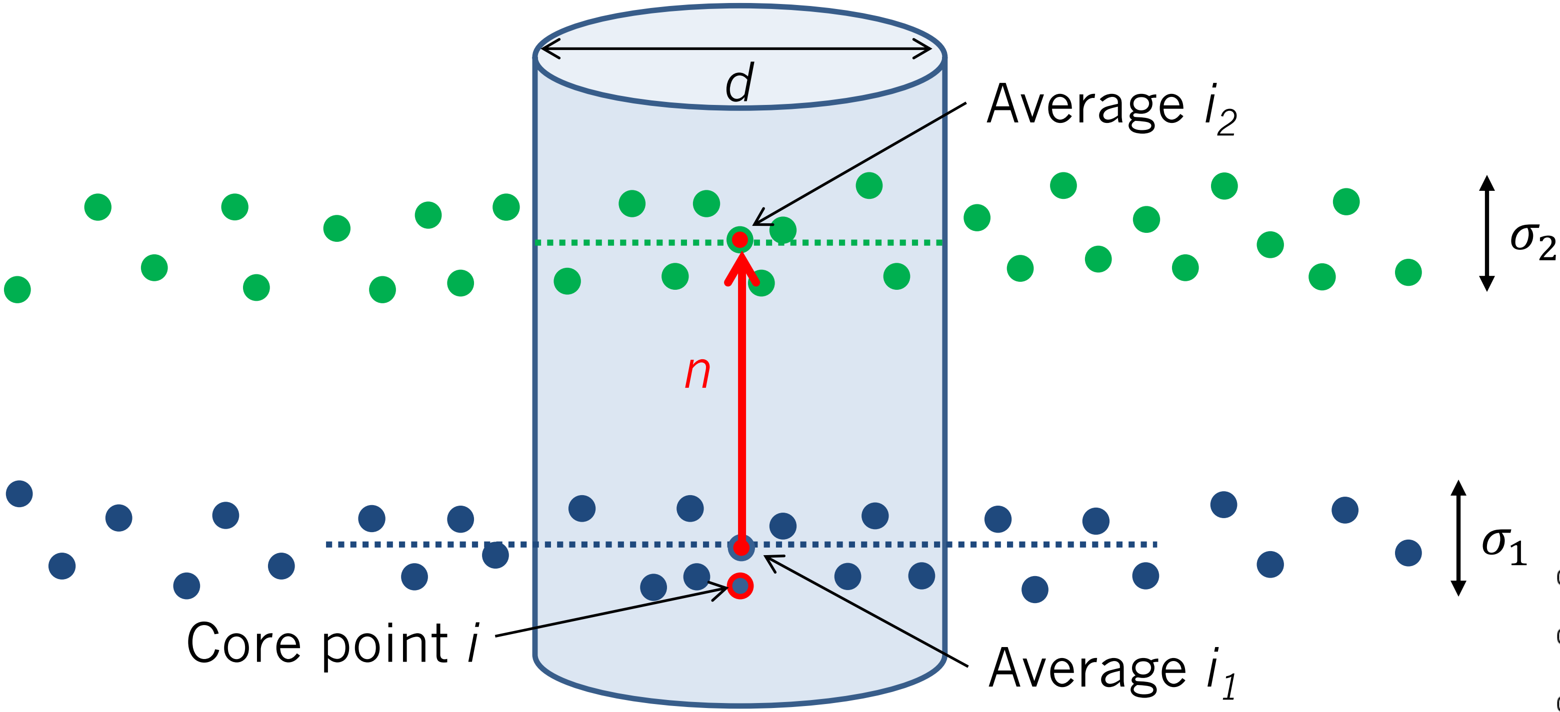


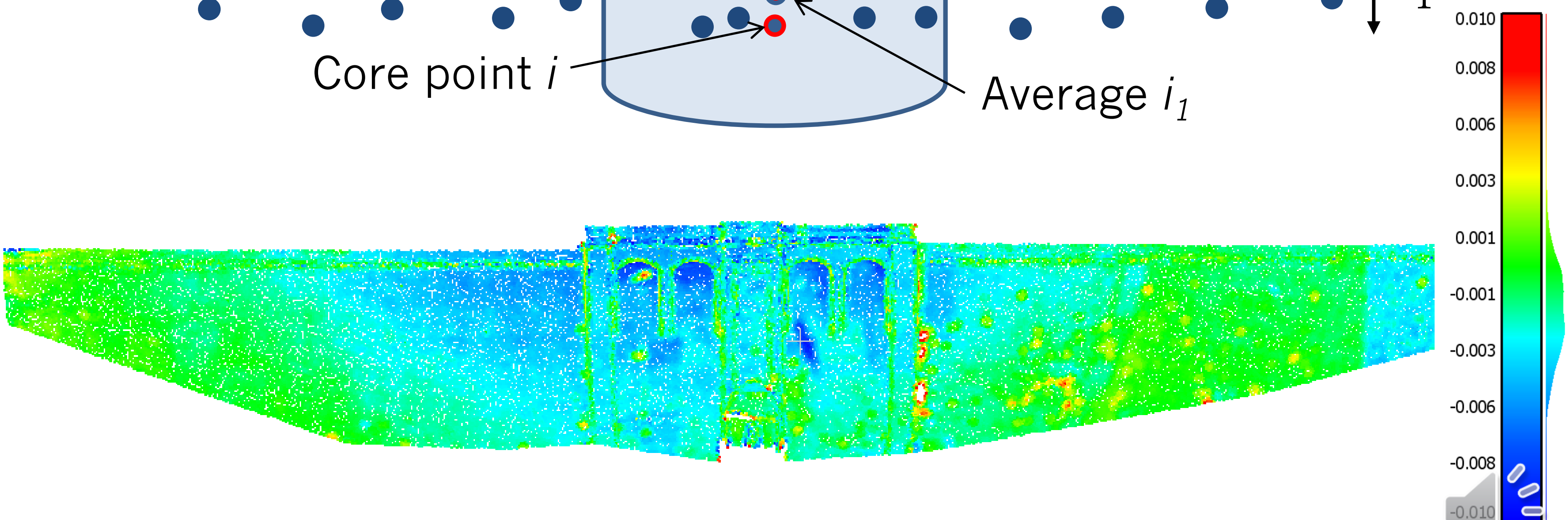
- Taking the complete point cloud or derived products (smoothed meshes, locally averaged points, free form surfaces, ...) as surface $\boldsymbol{x_t}$ representing the object

- Variant I) Finding corresponding surface points $\boldsymbol{x_t}$ and build differences: $\boldsymbol{d} = \boldsymbol{x_t} - \boldsymbol{x_{t-1}}$

- Variant II) Use corresponding surface points $\boldsymbol{x_t}$ to estimate transformation parameters between epochs (pot. small patches)

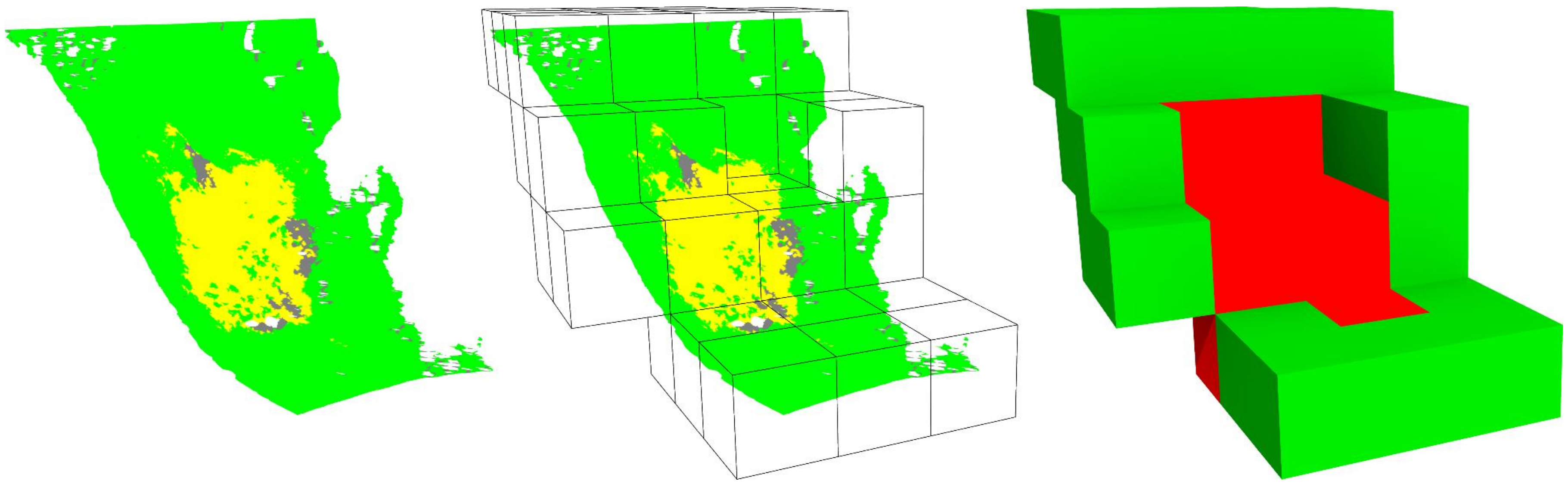
Example: M3C2





Example: segmentation and ICP

- Here: quarry face
- Yellow = cells with large transformation parameters



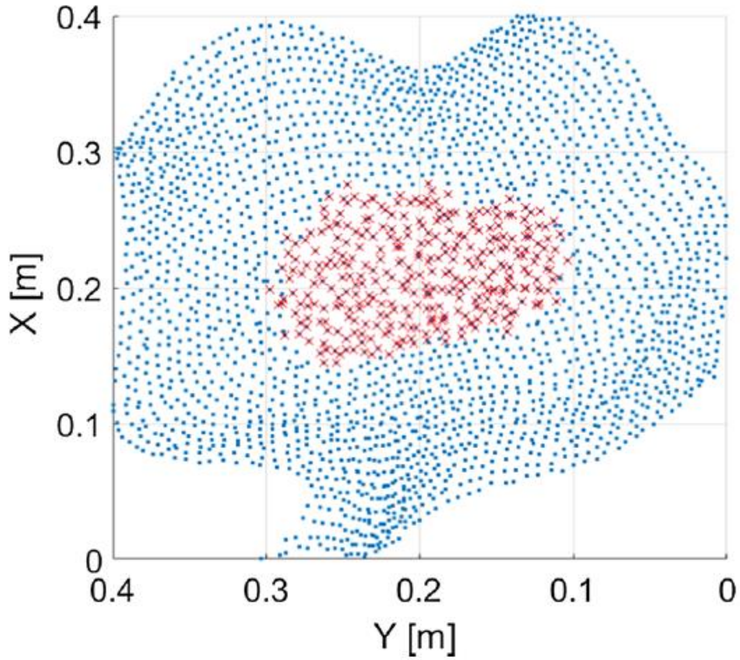
Courtesy: Daniel Wujanz

Example: stochastic modelling

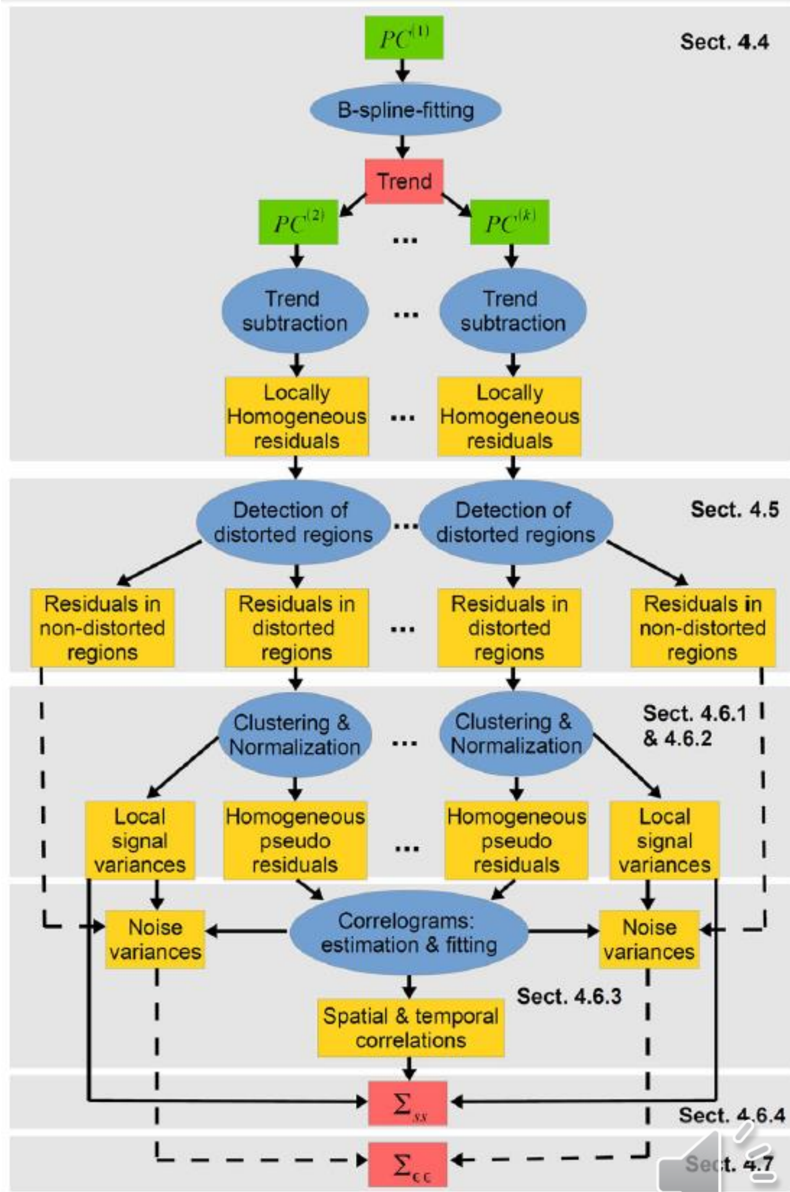
- Here: plant leaf

$$\boldsymbol{S}(u,v) = \sum_{i=0}^{n_p}\sum_{j=0}^{m_p} N_{i,p}(u)\cdot N_{j,q}(v)\cdot \boldsymbol{P}_{ij}$$

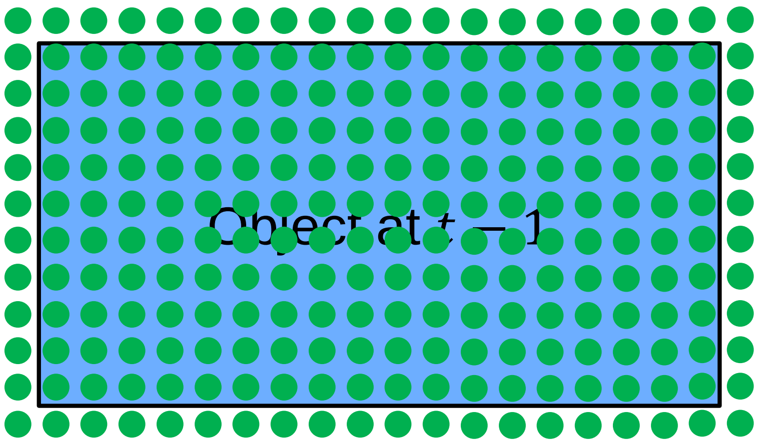
$$C(d_{ij}) = C_0 \cdot \exp\left(-\left(\frac{d_{ij}}{k}\right)^2\right)$$

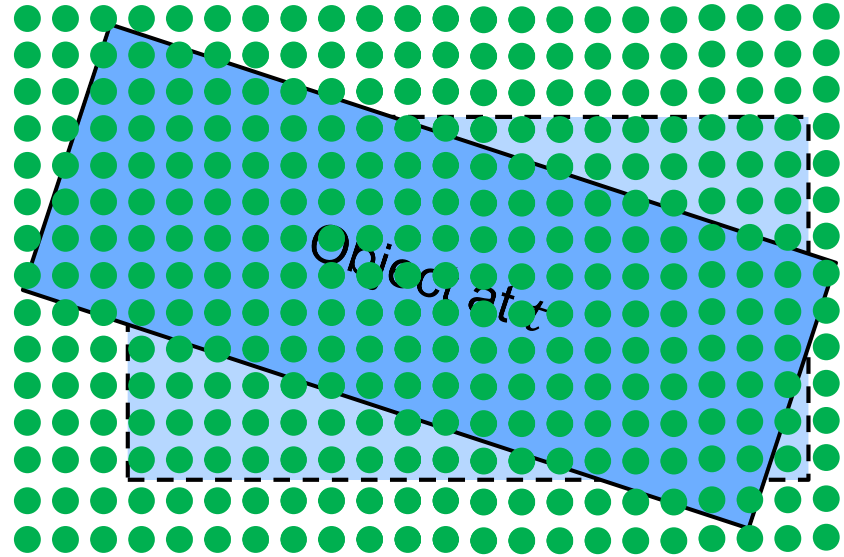


Courtesy: Corinna Harmening



B) Point based approach

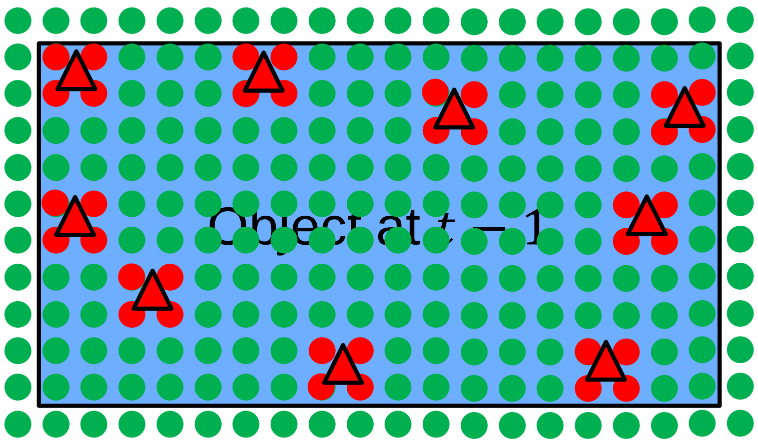


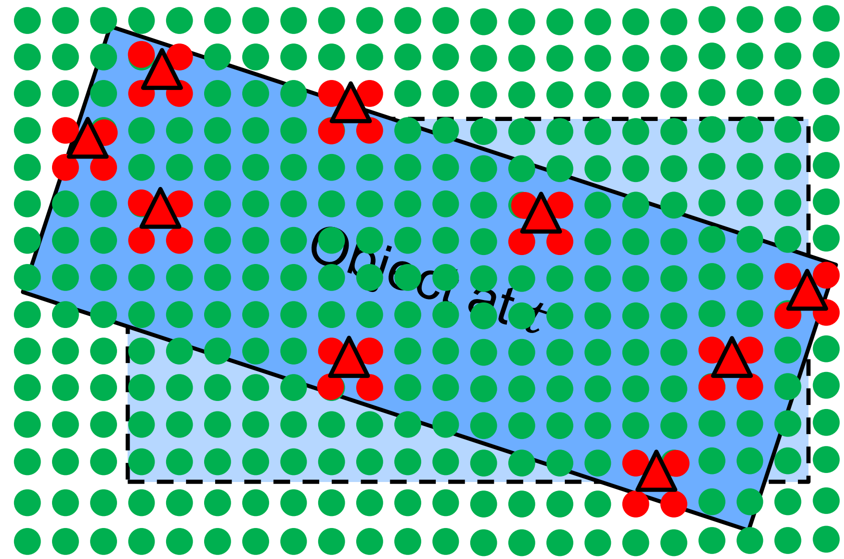


Characteristics of approach:

- Point cloud is reduced to selected points/features
- Individual points might be provided with semantic information
- Geometric changes only for individual points

B) Point based approach



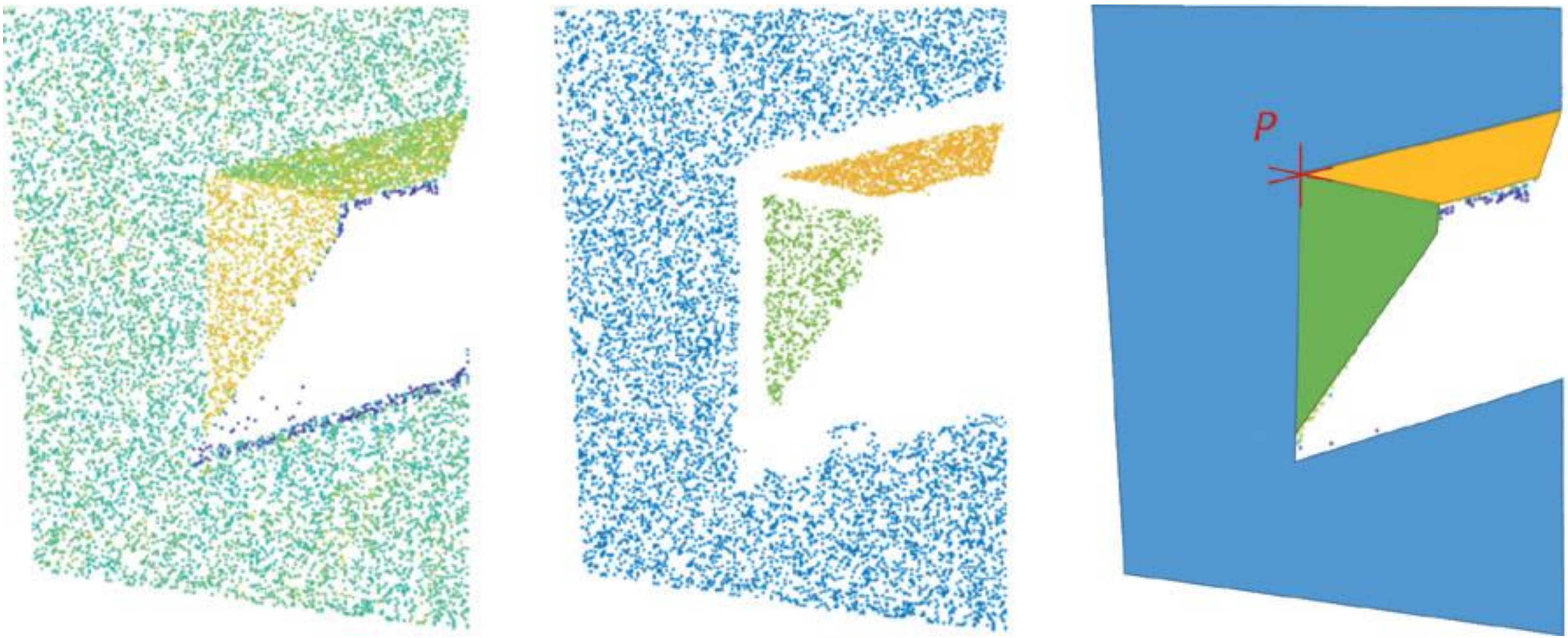


- Selecting/estimating individual points $\boldsymbol{x}_t$ with identifying features
- Matching these feature point between the epochs
- Building differences between matched feature points: $\boldsymbol{d} = \boldsymbol{x}_t - \boldsymbol{x}_{t-1}$

- Examples: F2S3 by Gojcic et al. (2020), Matching using geometric structures or images by Wunderlich et al. (2020)

Example: features at structures

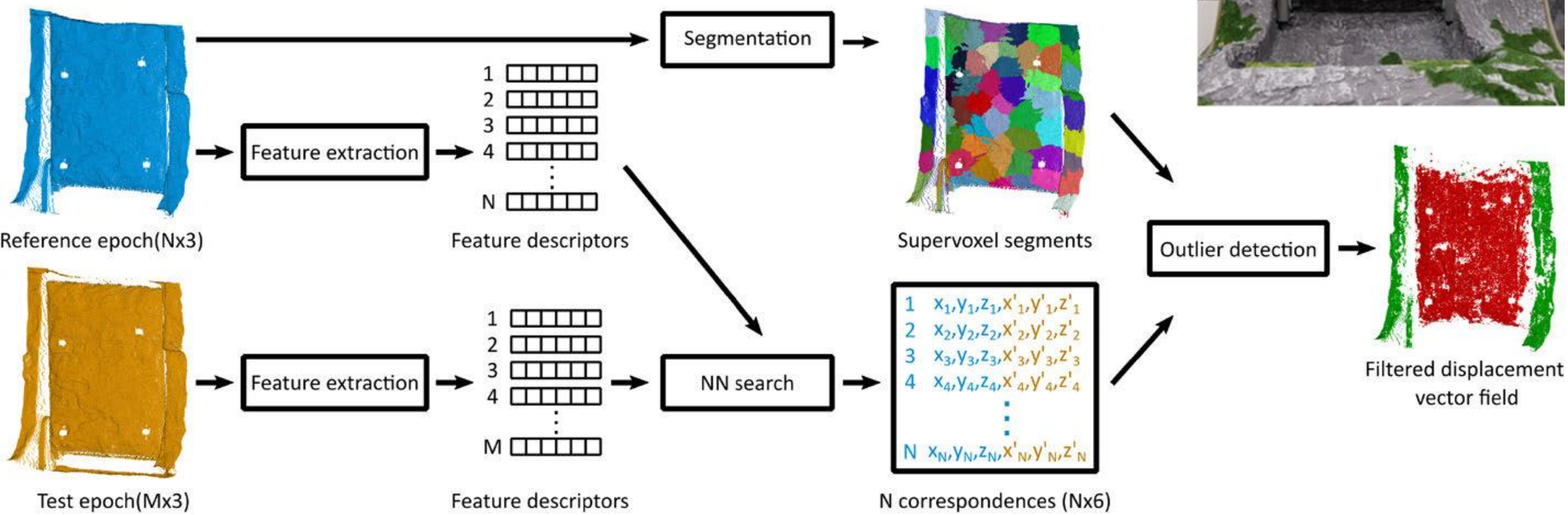
- Here: Window corner



Courtesy: Thomas Wunderlich

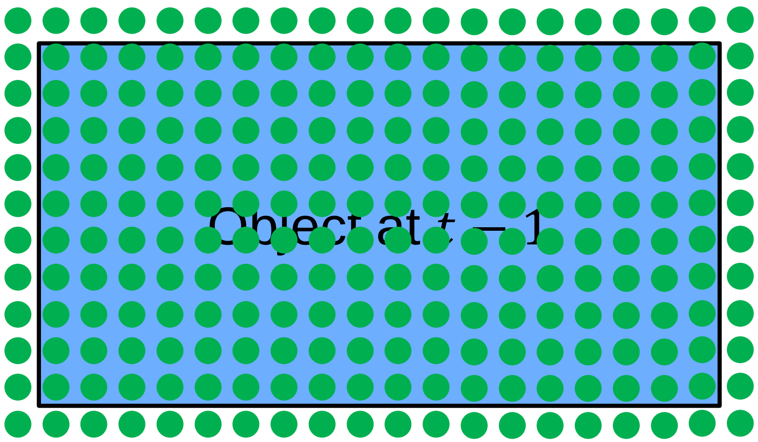
Example: features at environments

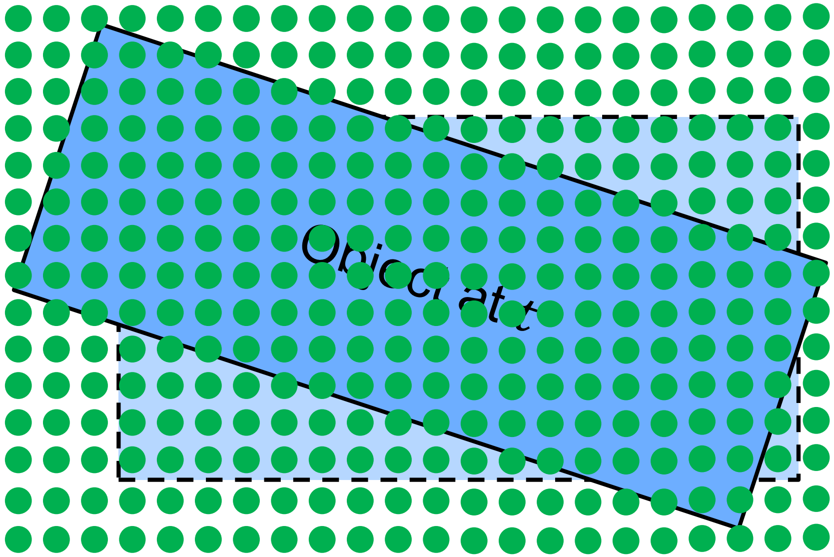
- Here: Rockfall (simulator)
- **F2S3**: deep learning methods with complex procedure



Courtesy: Zan Gojcic & Andreas Wieser

C) Parameter based approach

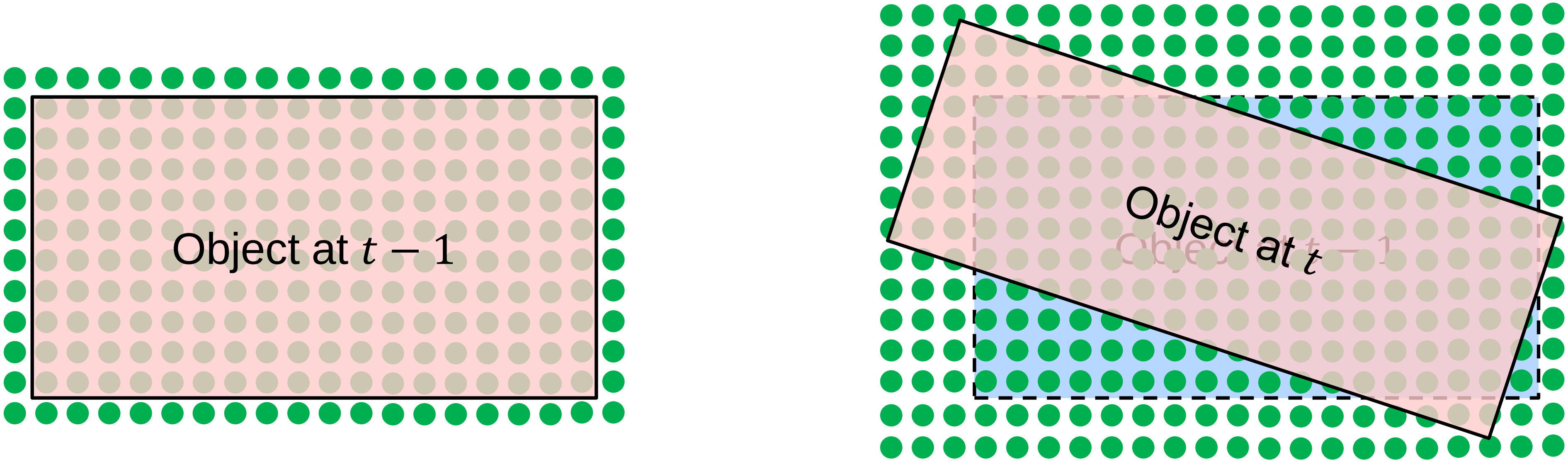




Characteristics of approach:

- Point cloud is geometrically parameterized in each epoch
- Parameterized object might be provided with semantic information
- Geometric changes only for parameterized objects

C) Parameter based approach

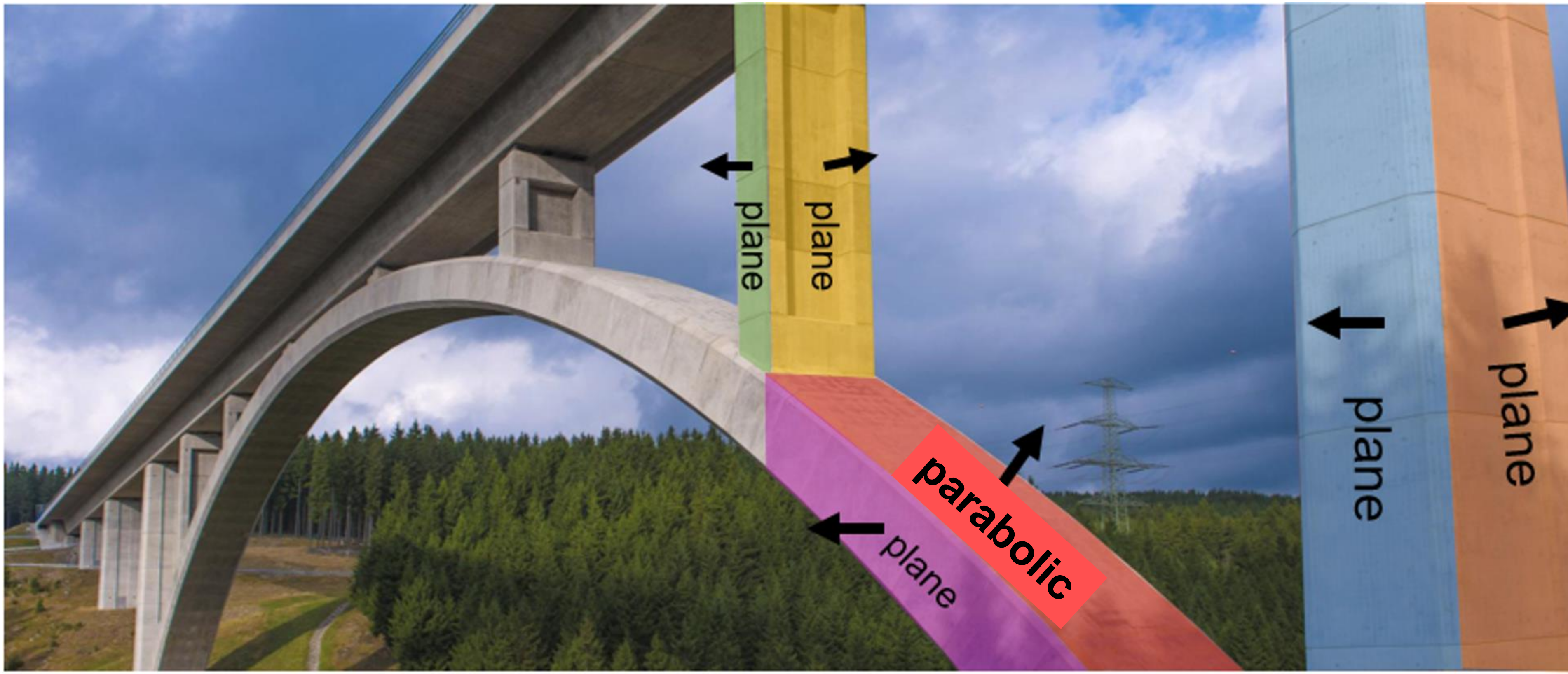


- Paramterizing the object with geometrically interpretable parameters $\boldsymbol{x_t}$ (e.g., plane, cylinder)
- Building differences between derived parameter: $\boldsymbol{d} = \boldsymbol{x_t} - \boldsymbol{x_{t-1}}$
- Variant: Segmenting the point cloud into several geometric interpretable objects

Example: geometric primitives

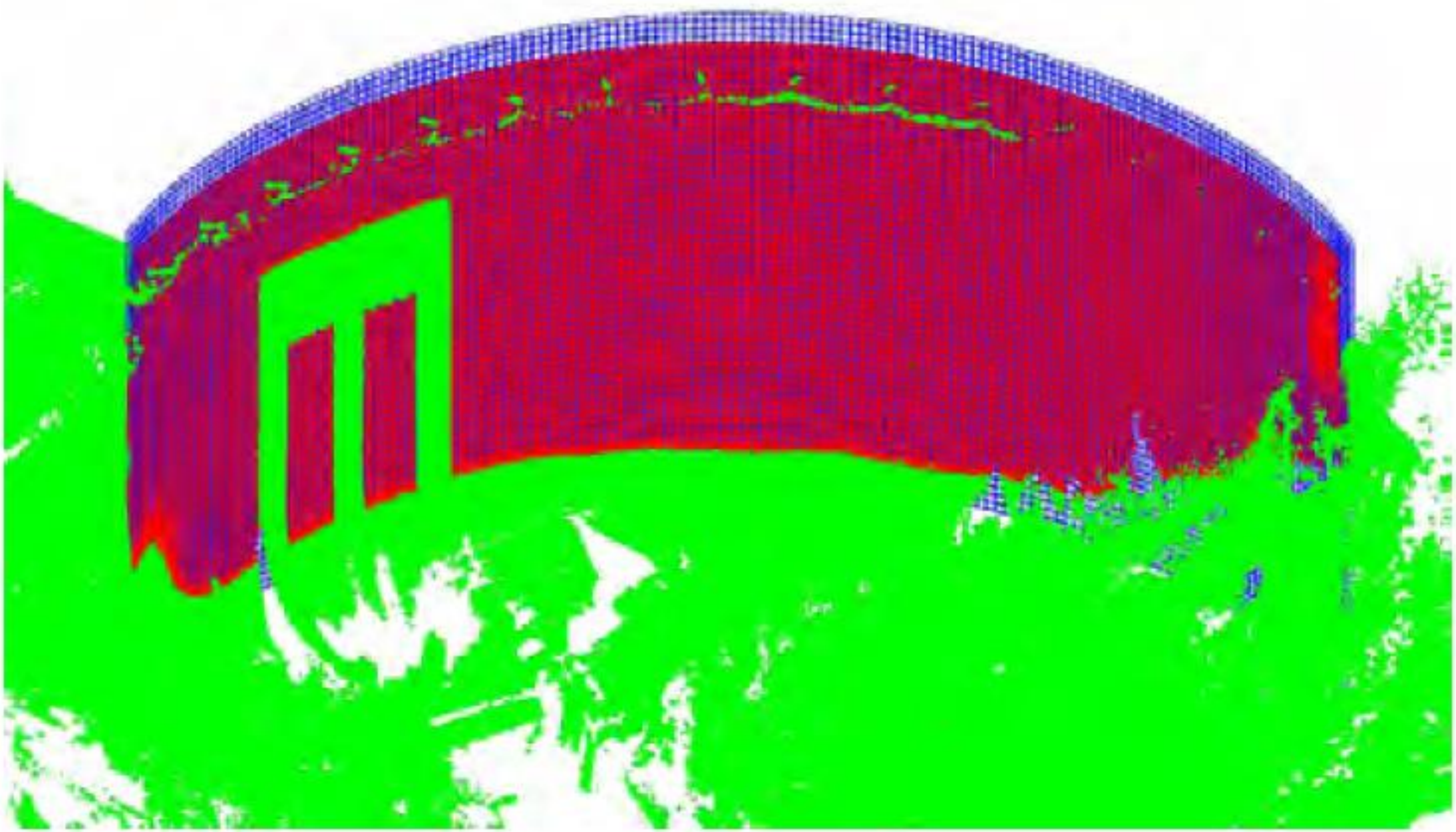
- Here: bridge

Courtesy: Thomas Wunderlich



Example: plane segementation

- Here: water dam



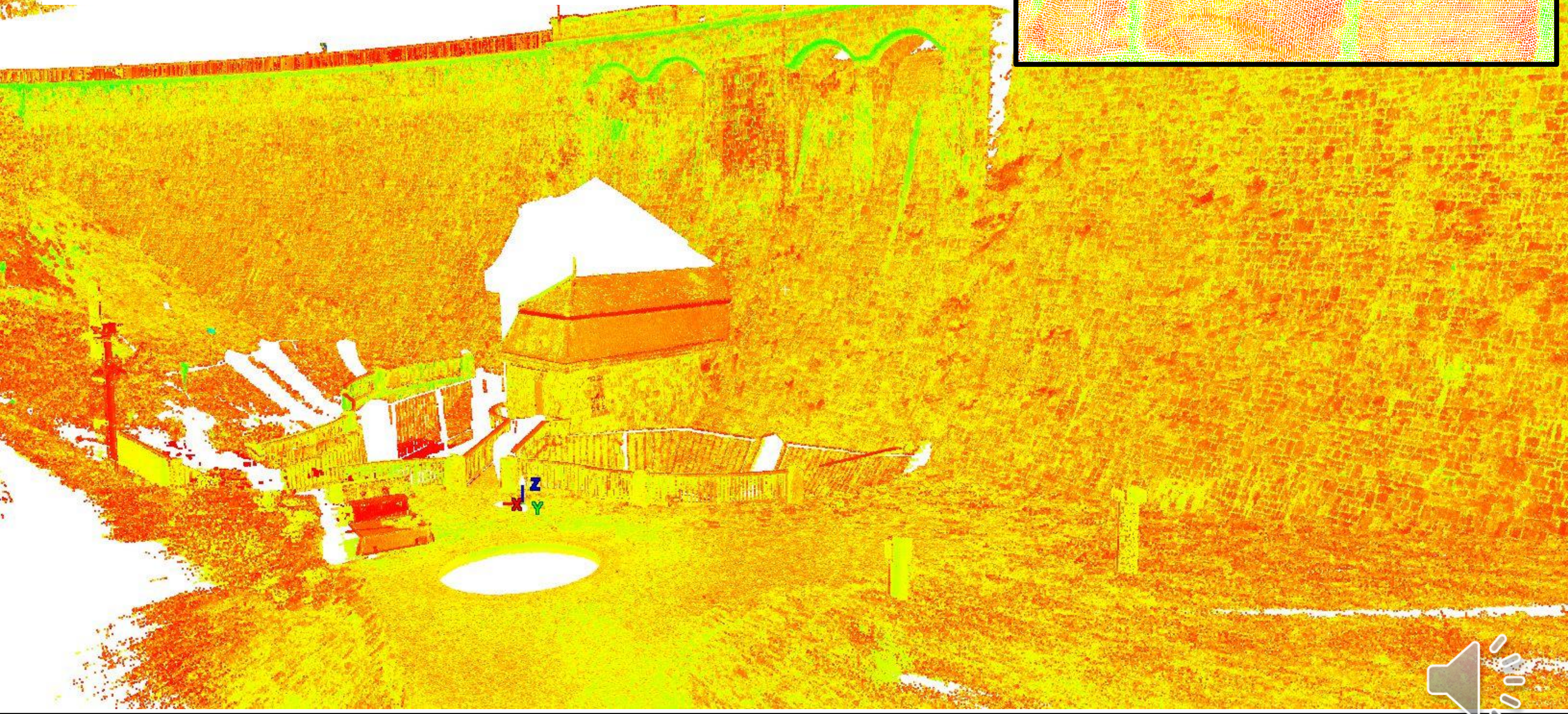
Courtesy: Dirk Eling

Approaches applied to dam

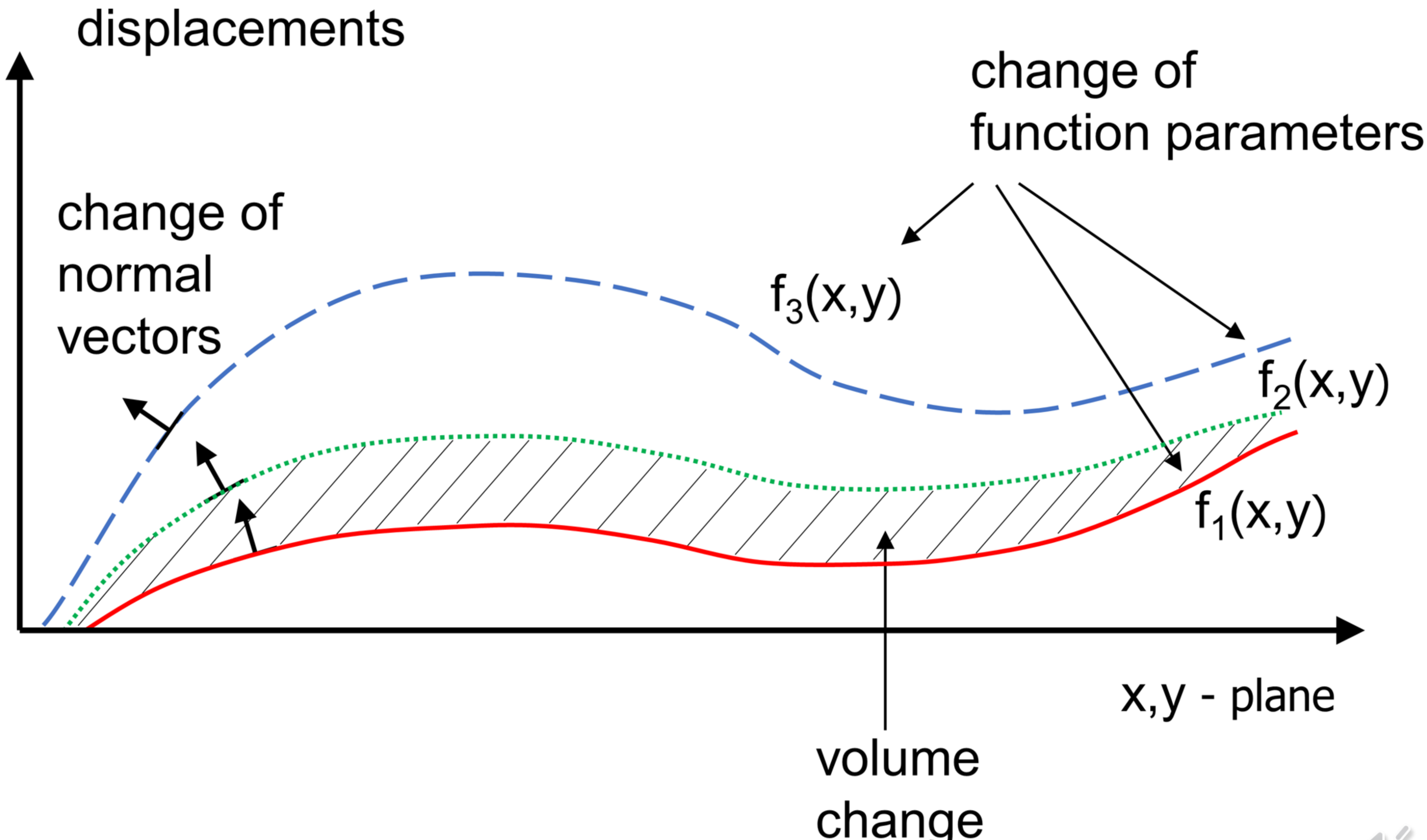
A) M3C2 or local ICP's

B) Features = rubblestones

C) Dam = hyperboloid or local planes



Overlap of approaches



Courtesy: Thomas Wunderlich

Agenda

7 Deformation analysis with point clouds

7.3 Approaches for revealing changes in point clouds

7.3.1 Problem statement

7.3.2 Introducing the approaches

7.3.3 Open challenges

I) Significance test

$$\boldsymbol{d} = \boldsymbol{x}_t - \boldsymbol{x}_{t-1}; \qquad \boldsymbol{\Sigma}_{dd} = \boldsymbol{\Sigma}_{xx,t} + \boldsymbol{\Sigma}_{xx,t-1}$$

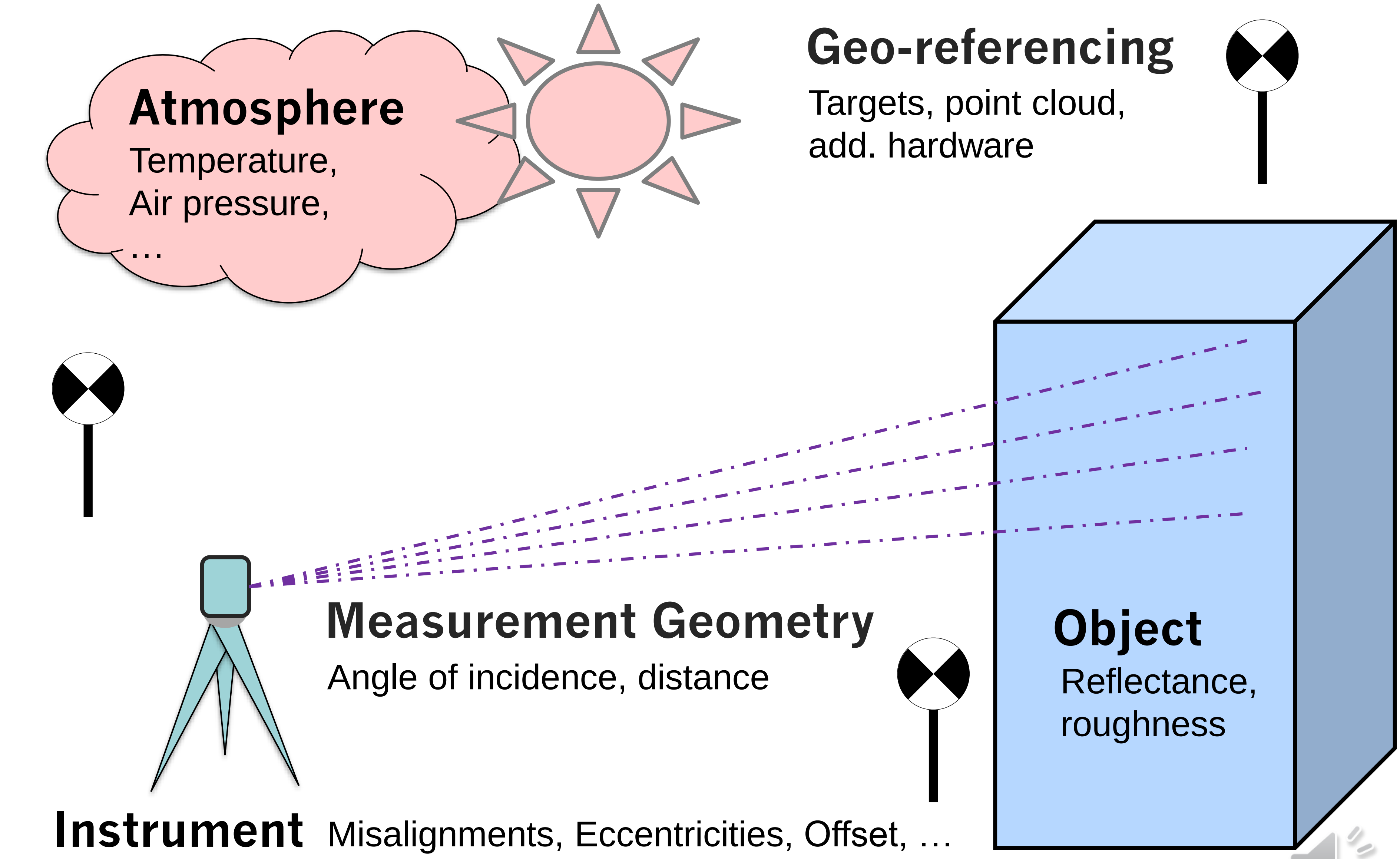
$$T_d = \frac{\boldsymbol{d}^T \boldsymbol{\Sigma}_{dd}^{-1} \boldsymbol{d}}{\operatorname{rank}(\boldsymbol{\Sigma}_{dd})} \geq F_{\operatorname{rank}(\boldsymbol{\Sigma}_{dd}),r,1-\alpha}$$

It all starts with:

- $\boldsymbol{\Sigma}_{xx}$ for $\boldsymbol{x}$ equals all points in point cloud, see last lecture

$$\boldsymbol{\Sigma}_{xyz} = \begin{bmatrix} \overbrace{\begin{bmatrix} \sigma_{x_1}^2 & \sigma_{y_1x_1} & \sigma_{z_1x_1} \\ \sigma_{x_1y_1} & \sigma_{y_1}^2 & \sigma_{z_1y_1} \\ \sigma_{x_1z_1} & \sigma_{y_1z_1} & \sigma_{z_1}^2 \end{bmatrix}}^{\boldsymbol{\Sigma}_{xyz,1,1}} & \cdots & \boldsymbol{\Sigma}_{xyz,m,1} \\ \vdots & \ddots & \vdots \\ \boldsymbol{\Sigma}_{xyz,1,m} & \cdots & \underbrace{\begin{bmatrix} \sigma_{x_m}^2 & \sigma_{y_mx_m} & \sigma_{z_mx_m} \\ \sigma_{x_my_m} & \sigma_{y_m}^2 & \sigma_{z_my_m} \\ \sigma_{x_mz_m} & \sigma_{y_mz_m} & \sigma_{z_m}^2 \end{bmatrix}}_{\boldsymbol{\Sigma}_{xyz,m,m}} \end{bmatrix}$$

Error sources at laser scanning



I) Significance test

$$\boldsymbol{d} = \boldsymbol{x}_t - \boldsymbol{x}_{t-1}; \qquad \boldsymbol{\Sigma}_{dd} = \boldsymbol{\Sigma}_{xx,t} + \boldsymbol{\Sigma}_{xx,t-1}$$

$$T_d = \frac{\boldsymbol{d}^T \boldsymbol{\Sigma}_{dd}^{-1} \boldsymbol{d}}{\text{rank}(\boldsymbol{\Sigma}_{dd})} \geq F_{\text{rank}(\boldsymbol{\Sigma}_{dd}),r,1-\alpha}$$

It all starts with:

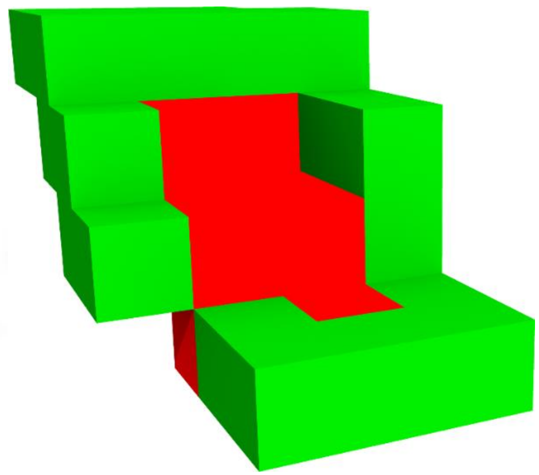
- $\boldsymbol{\Sigma}_{xx}$ for $\boldsymbol{x}$ equals all points in point cloud, see last lecture

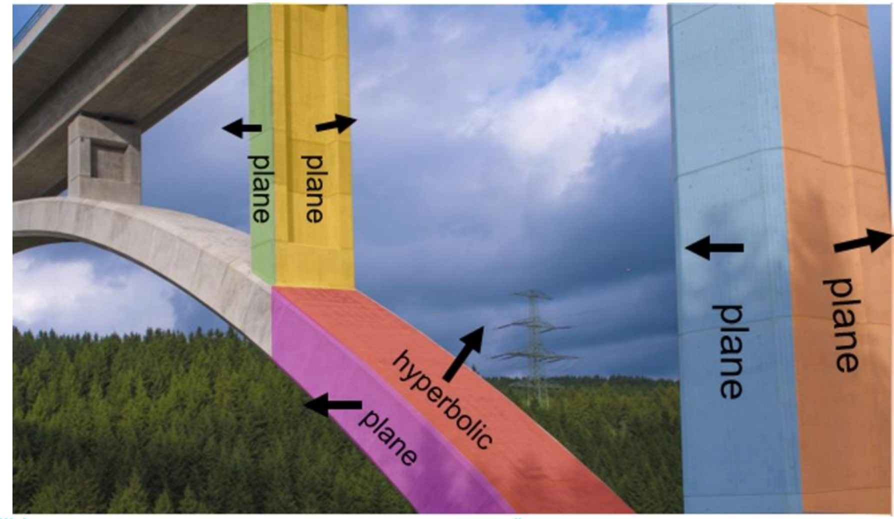
On top comes:

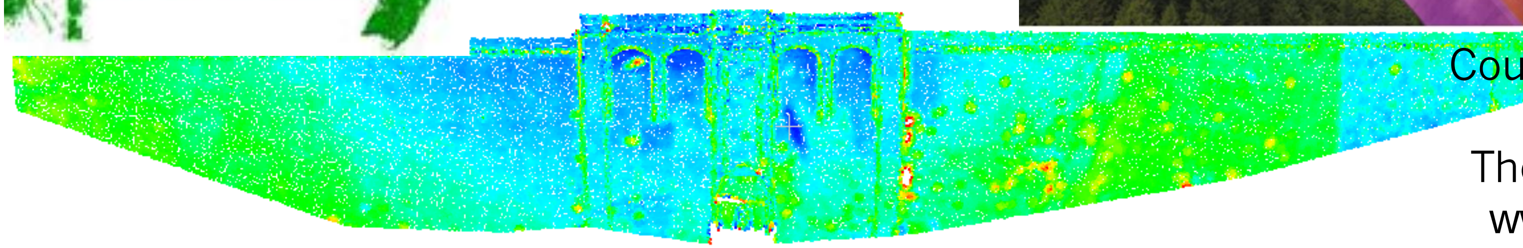
- A) Surface based: point $\boldsymbol{x}_t$ and $\boldsymbol{x}_{t-1}$ are not identical ones => discretization error (ARANEO, Wujanz 2019)
- B) Point based: uncertainty of features $\boldsymbol{x}_t$? => F2S3 (Gojcic et al. 2020), variance propagation?
- C) Parameter based: uncertainty of parameters $\boldsymbol{x}_t$ according to variance propagation accessible

=> Currently: Rather empirical determination of significance level

II) Interpretation

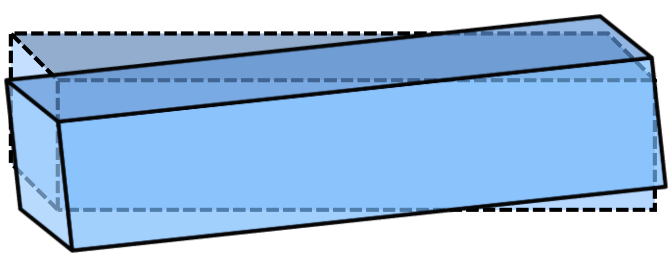


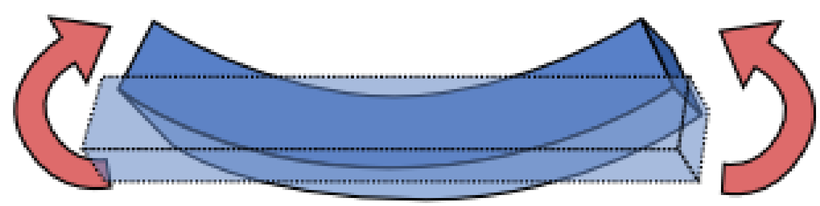




Courtesy: Zan Gojcic, Daniel Wujanz & Thomas Wunderlich, www.Maschinenbau-Wissen.de

- **Rigid body movement or shape deformation?**





=> Distinguishable only with semantic information

Interim summary

- Deformation analysis with point clouds is not straightforward: **no pre-selection & no semantic information**
- A) Surface based: build correspondences between complete point clouds and compare them
- B) Point based: reduce to identical points of smaller number and compare them
- C) Parameter based: parameterize geometrically and compare identical parameters

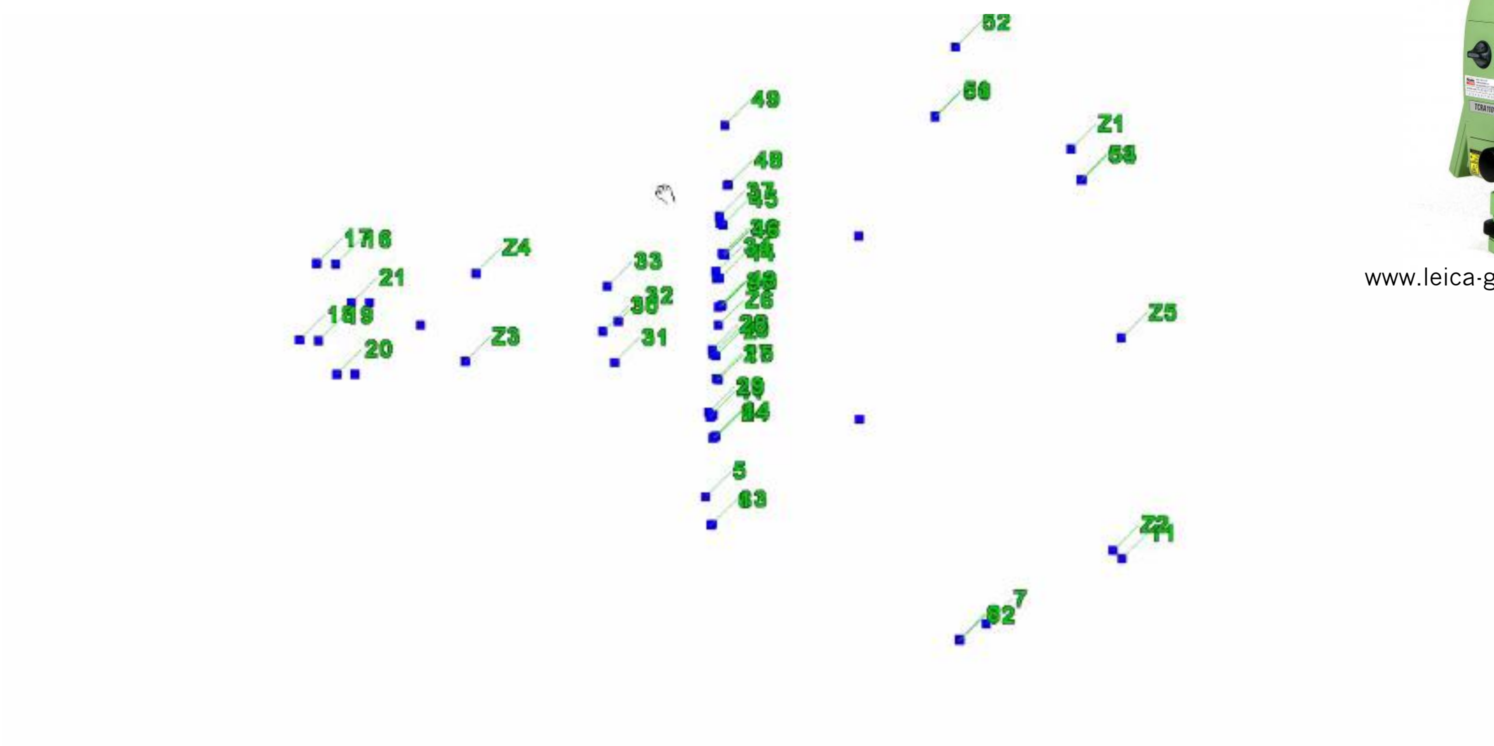
- For all: **realistic stochastic model seldomly existing, interpretation might be challenging**

7 Deformation analysis with point clouds

Total station: individual points

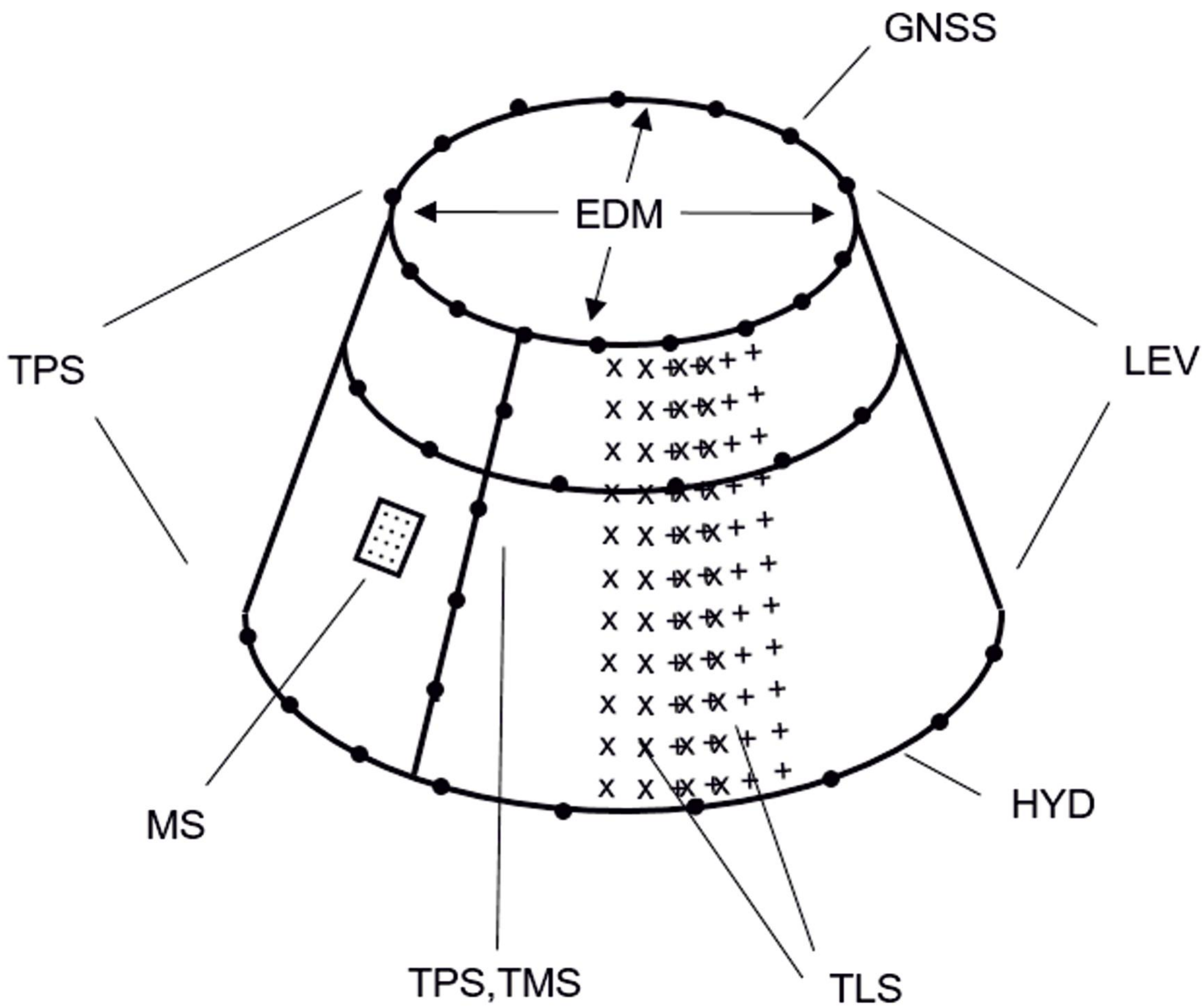
- Manually
- Few points, **pre-selected locations, semantic information given**
- **individual 3D points** (X,Y,Z)

=> Accuracy beats redundancy



www.leica-geosystems.com

Decade-long used sensors

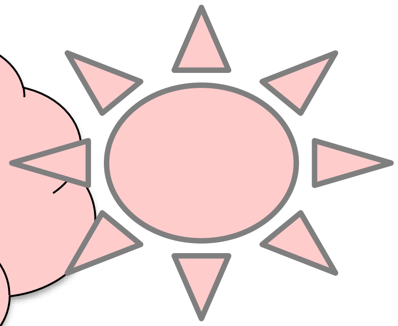


www.leica-geosystems.com, www.trimble.com/

Courtesy: Thomas Wunderlich

Error sources at laser scanning

Atmosphere
Temperature,
Air pressure,
…



Geo-referencing
Targets, point cloud,
add. hardware

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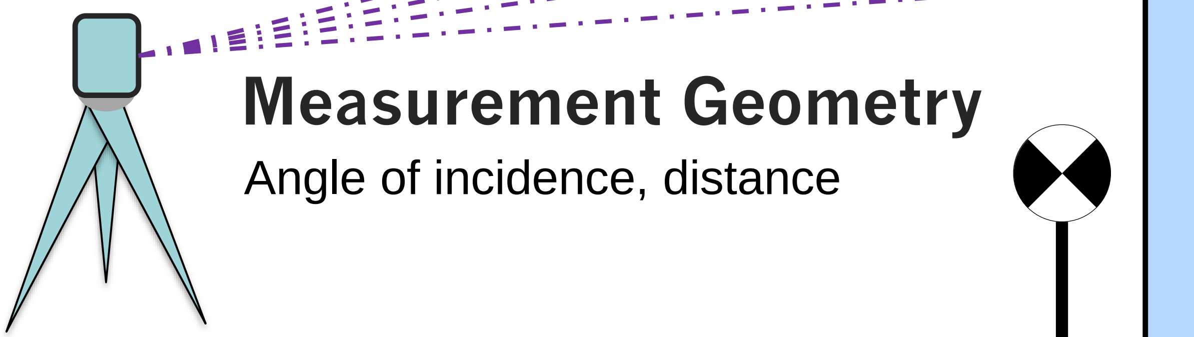
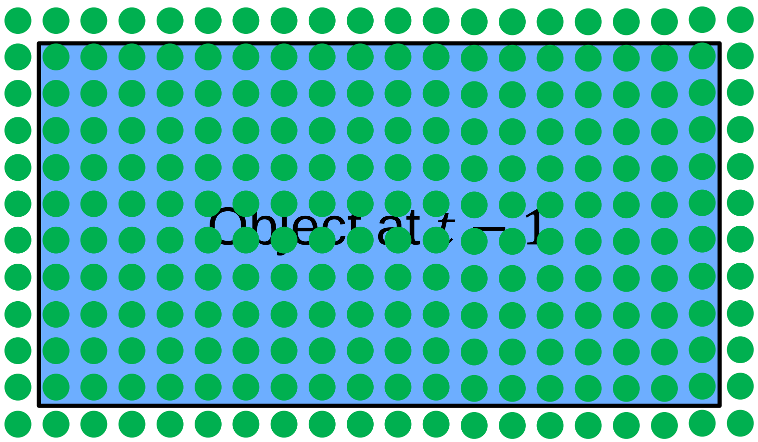


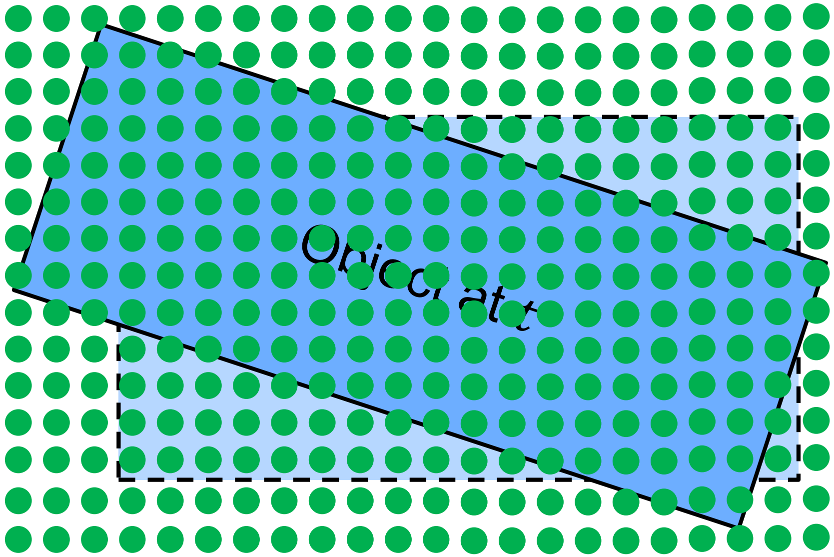
Measurement Geometry
Angle of incidence, distance

Instrument Misalignments, Eccentricities, Offset, …

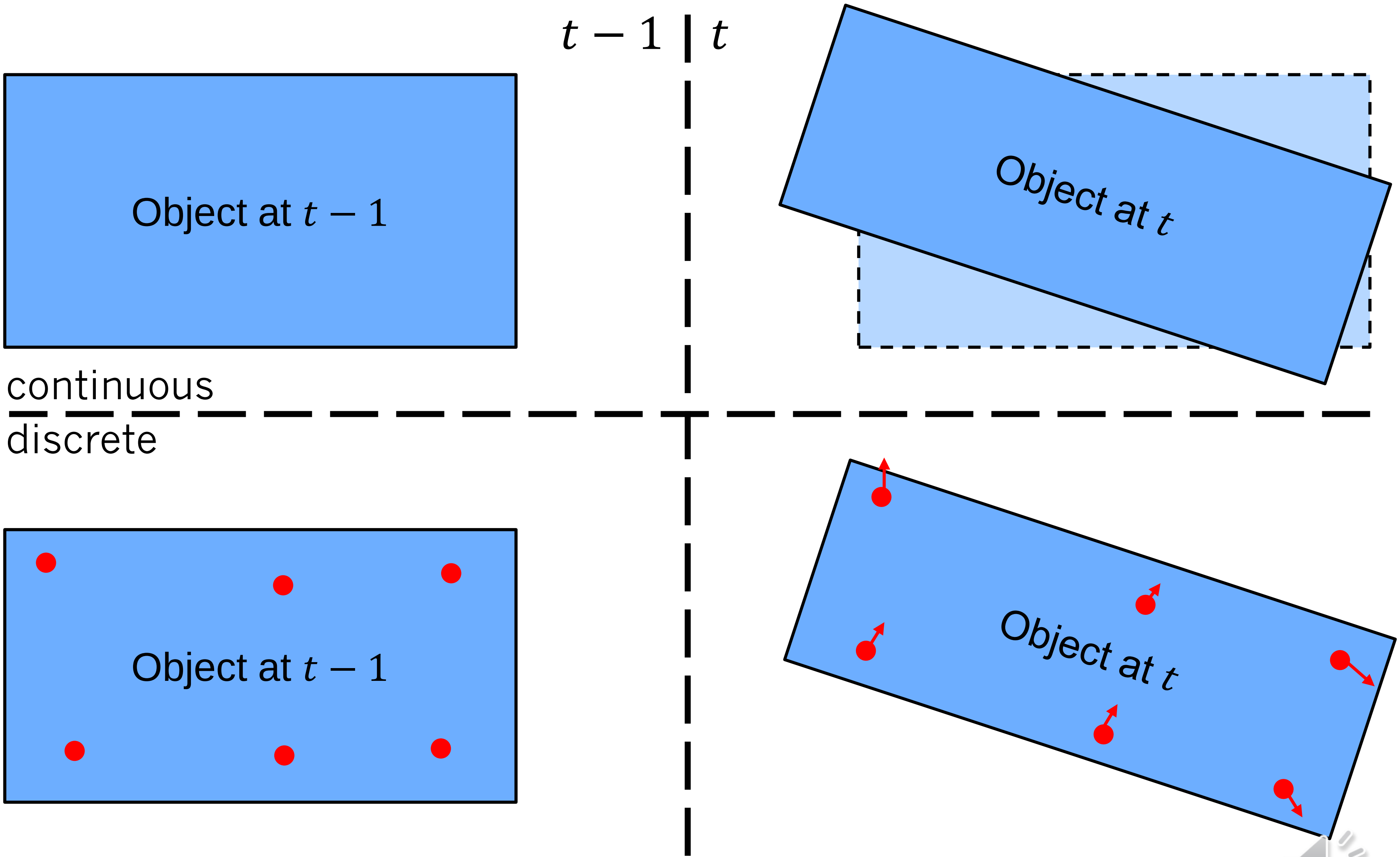
7 Deformation analysis with point clouds

General proceeding

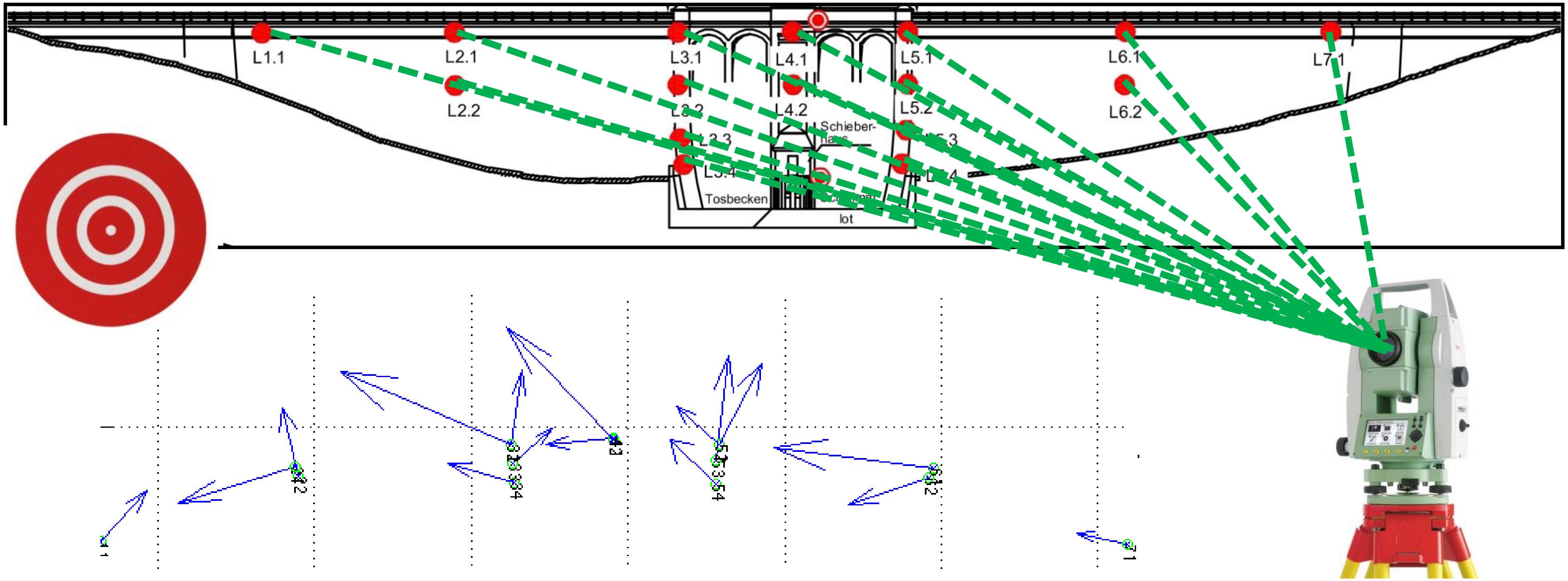




General proceeding



Applied to dam



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- x_t **are pre-selected positions on object with semantic information and kown uncertainty** Σ_{xx}

$$\boldsymbol{d} = \boldsymbol{x}_t - \boldsymbol{x}_{t-1}; \qquad \boldsymbol{\Sigma}_{dd} = \boldsymbol{\Sigma}_{xx,t} + \boldsymbol{\Sigma}_{xx,t-1}; \quad T_d = \frac{\boldsymbol{d}^T \boldsymbol{\Sigma}_{dd}^{-1} \boldsymbol{d}}{\mathrm{rank}(\boldsymbol{\Sigma}_{dd})} \geq F_{\mathrm{rank}(\boldsymbol{\Sigma}_{dd}),r,1-\alpha}$$

- Rigid body movement and shape deformation distinguishable by relative movement of individual points within each object

7 Deformation analysis with point clouds

7.5 Relation to engineering geodesy

7.5.1 Sensors used in engineering geodesy

7.5.2 Simplifying the deformation analyses

7.5.3 Pros and Cons

Pros and cons

Category	Point cloud	Individual points
Data acquisition	Automatic and fast	Manual and slow
Objectivity of data	High	Low
Semantic information	Searched	Given
Level of detail	High	Low
Data processing	Tricky + individual	Straightforward
Interpretation of results	Manipulable	Standardized

7 Deformation analysis with point clouds

7.6 Summary

Summary

- Point clouds contain lots of geometric information that can be analyzed for deformations
- Dependent on objectives, different models to choose
- But two properties complicate the analysis:

  1) Position of points is not pre-selected & points do not have a semantic information

  => Different approaches to find correspondences / identities between epochs

  2) Uncertainty of points is not assessible straightforward

  => Significance of deformation not easy to assess

- ... ongoing process

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Learning objectives

- What is a deformation analysis?
- How to perform a deformation analysis with point clouds?
- What are the challenges?