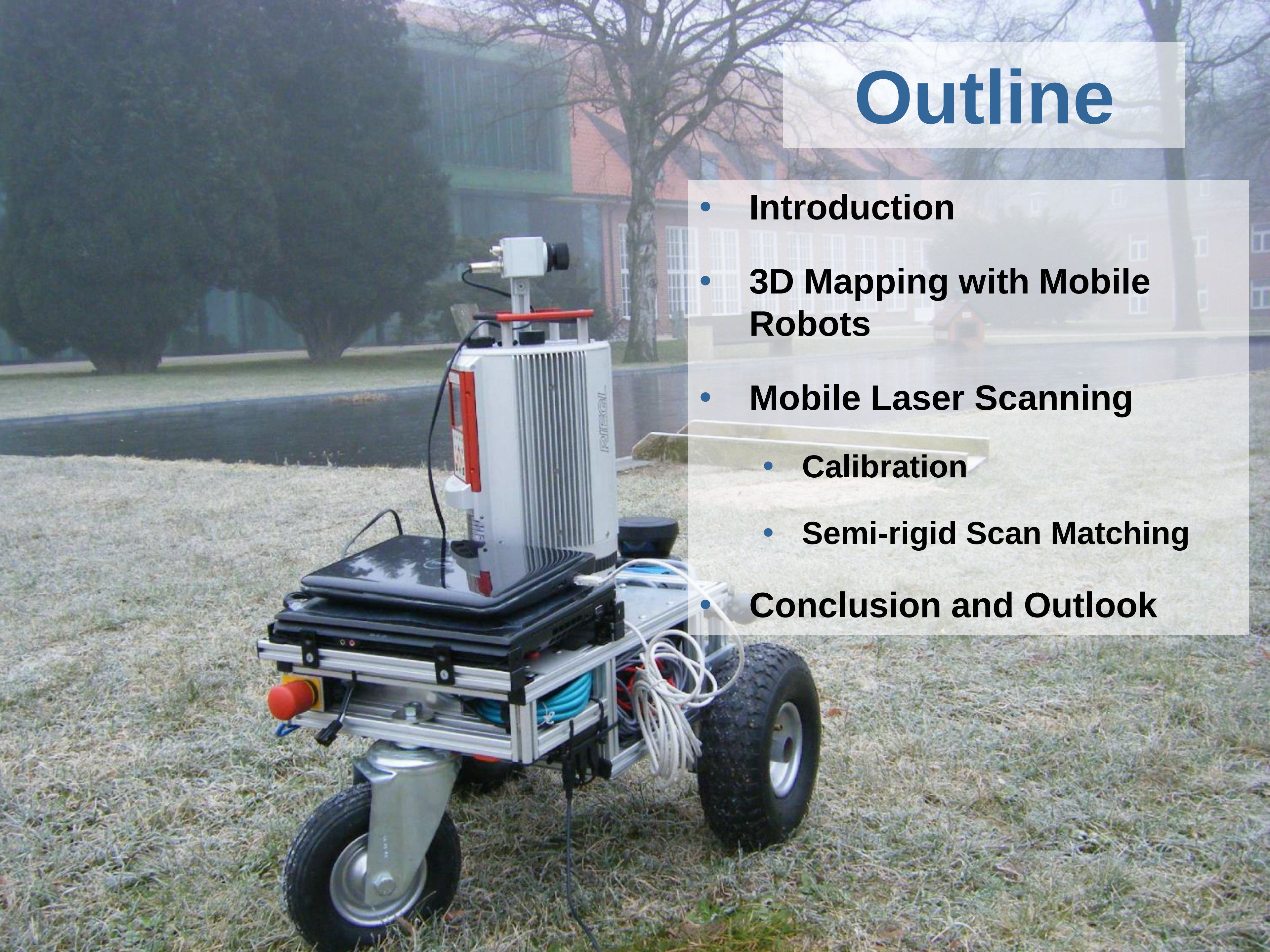
Optimal 3D Point Clouds from Mobile Laser Scanning

The image depicts how our robot Irma3D sees itself in a mirror. The laser looking into itself creates distortions as well as changes in intensity that give the robot a single eye, complete with iris and pupil. Thus, the image is called "Self Portrait with Duckling".

Prof. Dr. Andreas Nüchter

About this talk…

(video)



Outline

- Introduction
- 3D Mapping with Mobile Robots
- Mobile Laser Scanning
  - Calibration
  - Semi-rigid Scan Matching
- Conclusion and Outlook

Outline

- **Introduction**
- 3D Mapping with Mobile Robots
- Mobile Laser Scanning
  - Calibration
  - Semi-rigid Scan Matching
- Conclusion and Outlook

The Ariadne Robot (2002/2003)

First, we used the 3D information for obstacle avoidance. Later of we did initial 3D mapping experiments.

The motion of the robot
3 DoF

(Video Crash) (Video NoCrash)


RoboCup
-11 July
stanbul
HOSTED BY
RoboCup
BOĞAZİÇİ ÜNİVERSİTESİ
1863
EVG
Sankt Augustin
Hendrik
EVG
Sankt Augustin
EVG
Sankt Augustin
EVG
Sankt Augustin

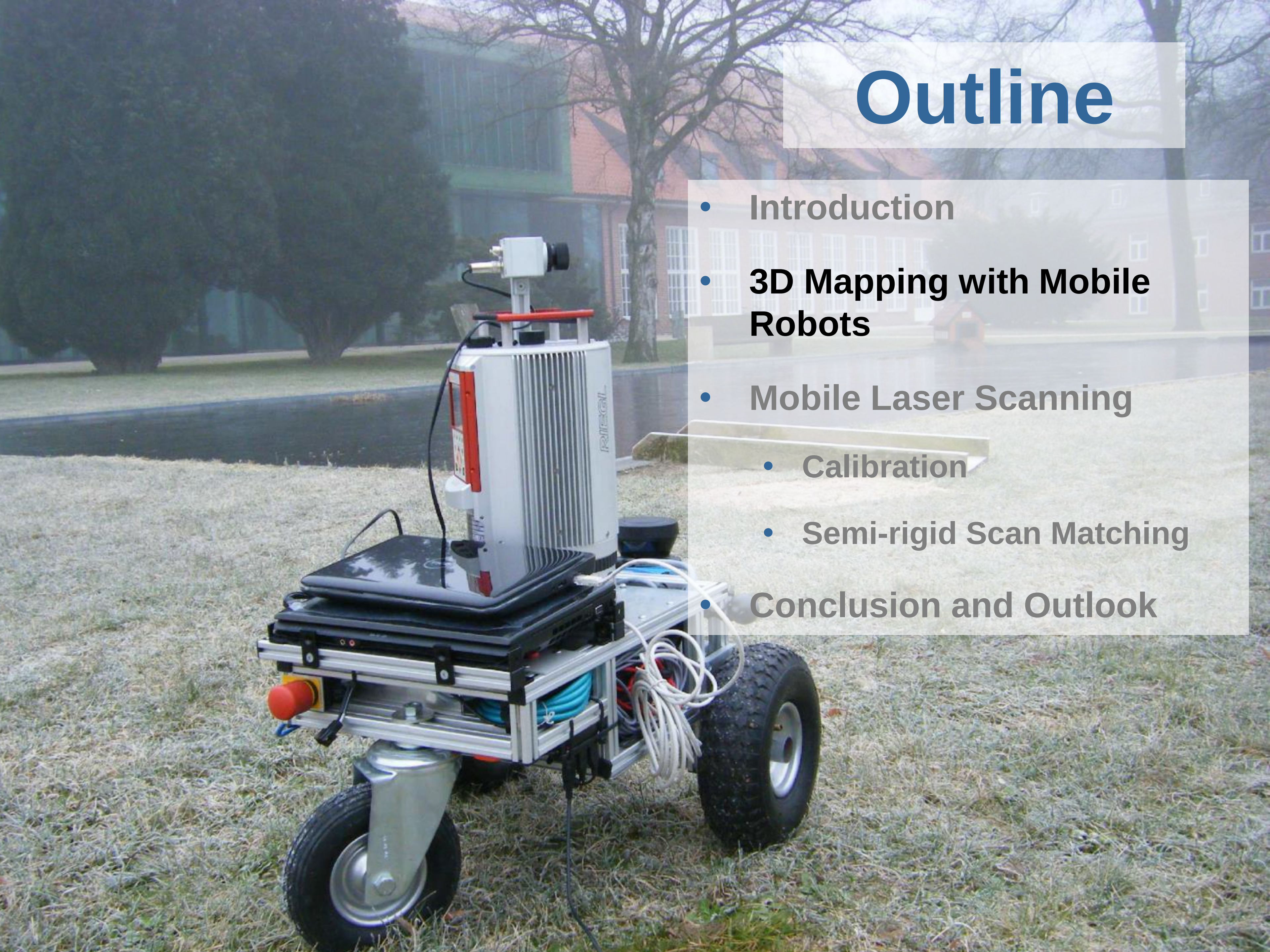
The Mobile Robot Irma3D (since 2010)

- Automation of 3D scanning

(video)

(video)

  – Combination of terrestrial / kinematic laser scanning



Outline

- Introduction
- **3D Mapping with Mobile Robots**
- Mobile Laser Scanning
  - Calibration
  - Semi-rigid Scan Matching
- Conclusion and Outlook

The ICP Algorithm

Scan registration Put two independent scans into one frame of reference

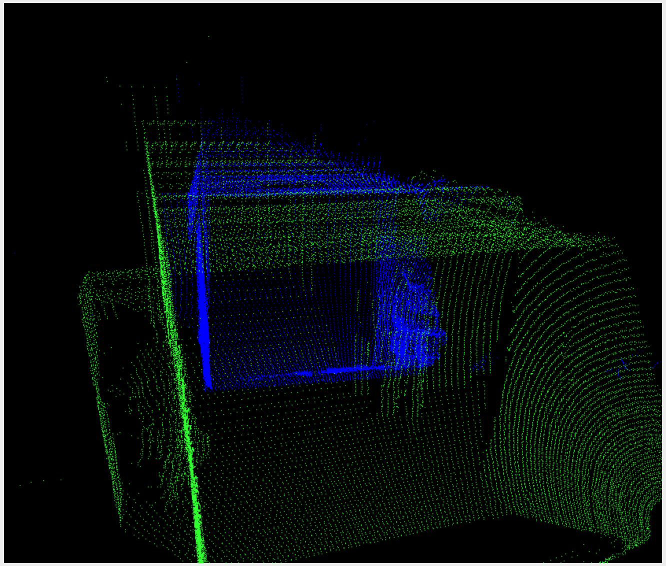
Iterative Closest Point algorithm [Besl/McKay 1992]

For prior point set M ("model set") and data set D

1. Select point correspondences
2. Minimize for rotation $\mathbf{R}$, translation $\mathbf{t}$

$$E(\mathbf{R}, \mathbf{t}) = \frac{1}{N} \sum_{i=1}^{N} ||\mathbf{m}_i - (\mathbf{R}\mathbf{d}_i + \mathbf{t})||^2$$

3. Iterate **1.** and **2.**

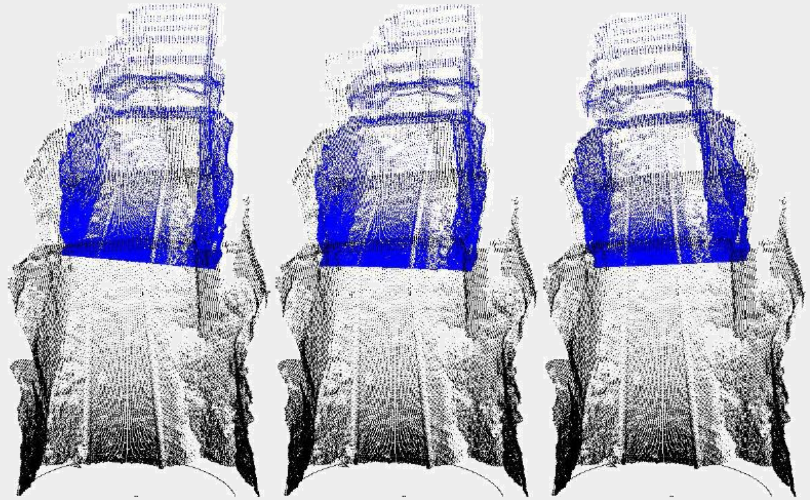


Four closed form solution for the minimization

- works in 3 translation plus 3 rotation dimensions

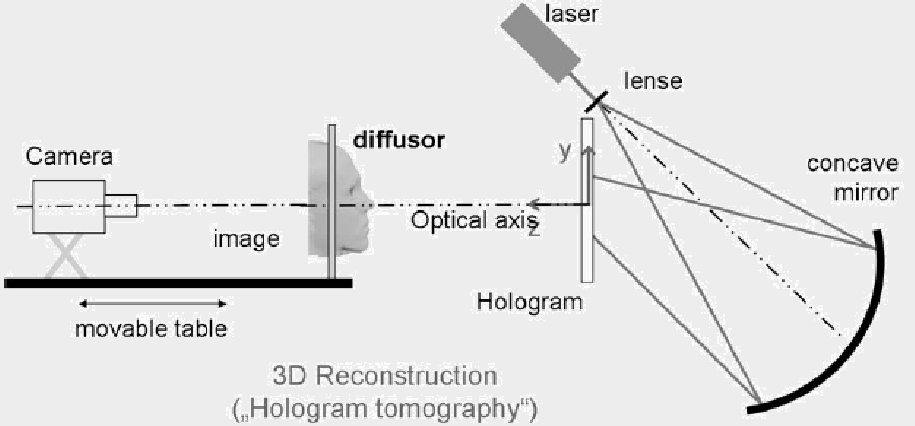
3D Mapping Examples

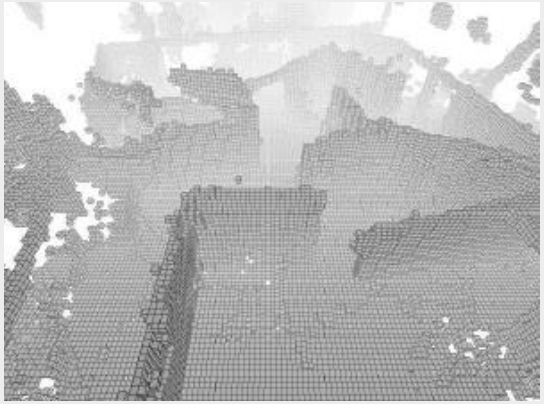
CMU 3D mapping of abandoned mines



RoboCup Rescue

3D reconstruction in the context of medical imaging





The ICP Algorithm / globalICP Algorithm

Scan registration Put two independent scans into one frame of reference

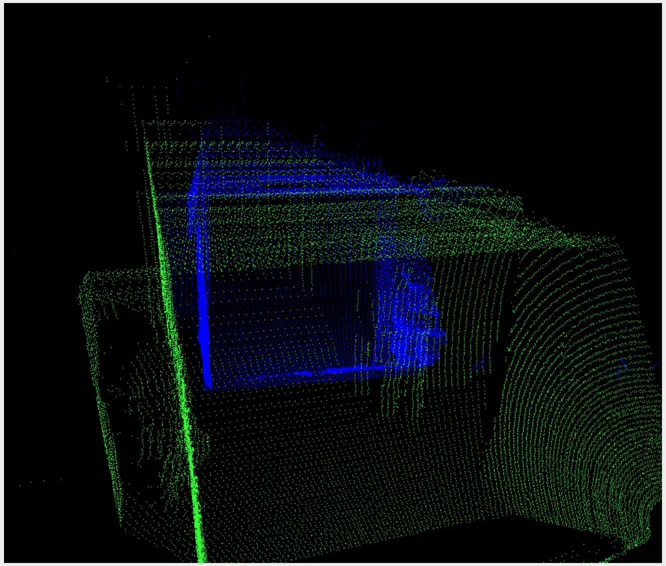
Iterative Closest Point algorithm [Besl/McKay 1992]

For prior point set M (“model set”) and data set D

1. Select point correspondences
2. Minimize for rotation $\mathbf{R}$, translation $\mathbf{t}$

$$E(\mathbf{R}, \mathbf{t}) = \frac{1}{N} \sum_{i=1}^{N} ||\mathbf{m}_i - (\mathbf{R}\mathbf{d}_i + \mathbf{t})||^2$$

3. Iterate **1.** and **2.**



Four closed form solution for the minimization

Global consistent registration

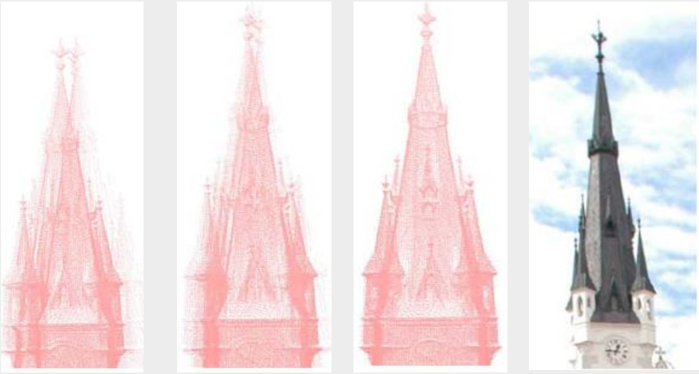
$$E = \sum_{j \to k} \sum_i |\mathbf{R}_j \mathbf{m}_i + \mathbf{t}_j - (\mathbf{R}_k \mathbf{d}_i + \mathbf{t}_k)|^2$$

Example of high-precise registrations

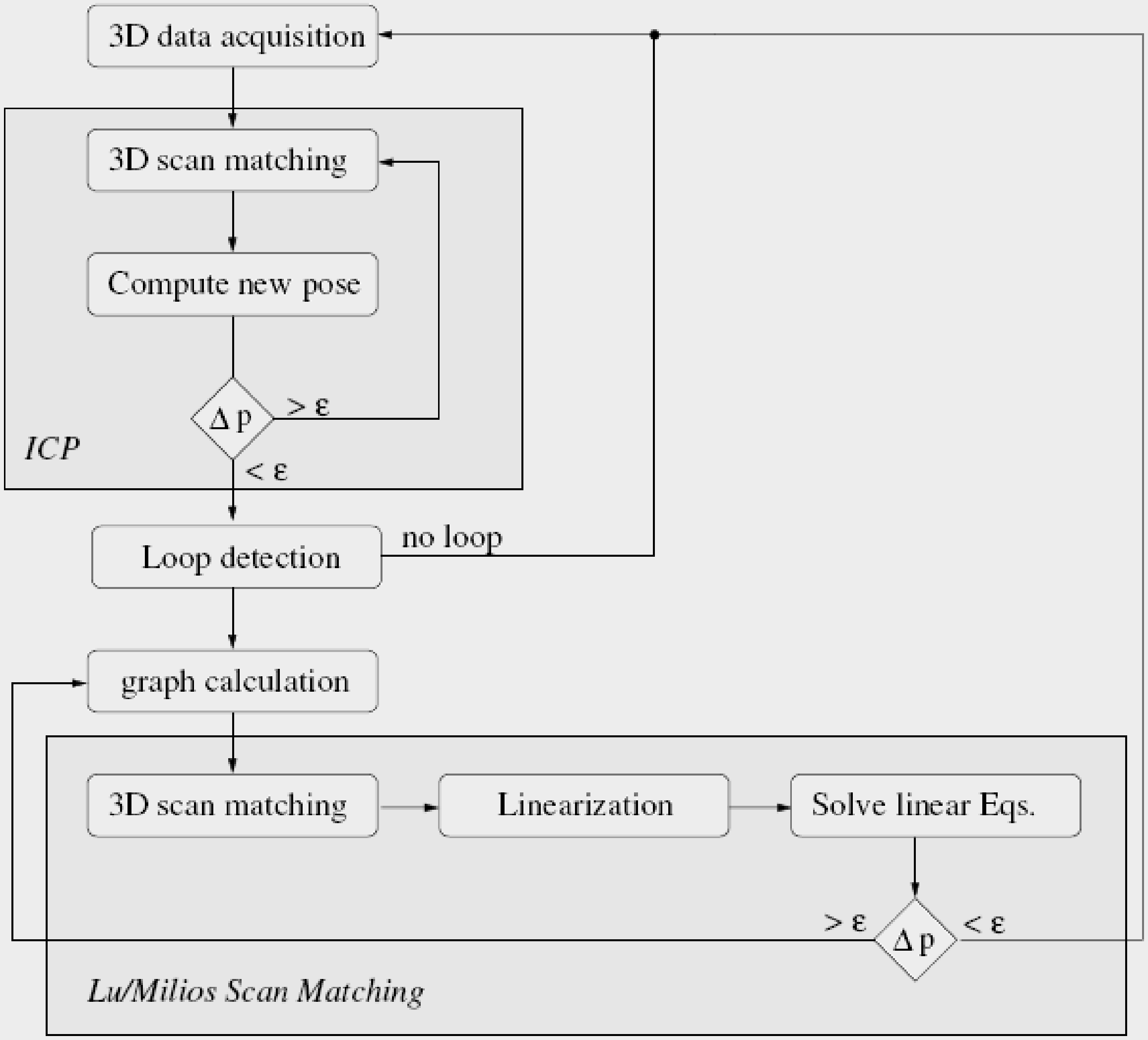
- Riegl Laser Measurement GmbH

(Video courtesy of Riegl)

(Video 1) (Video 2) (Video 3)

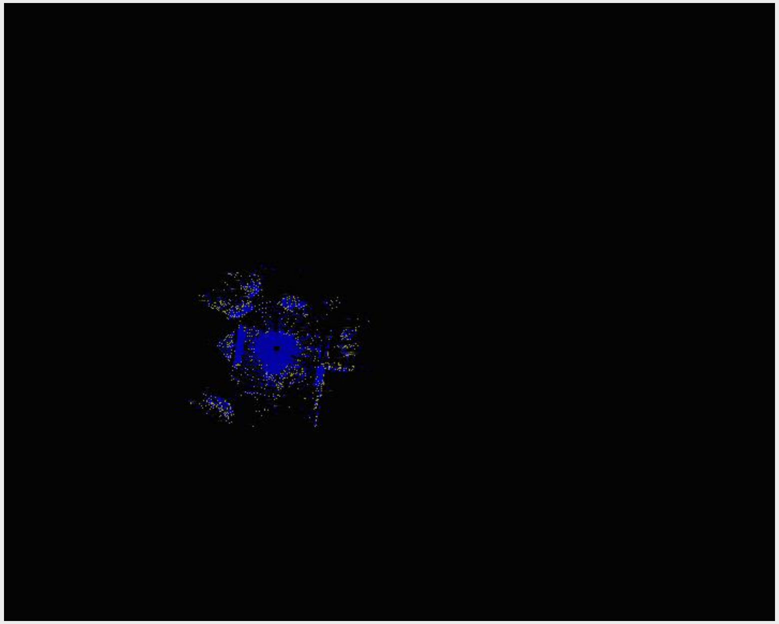


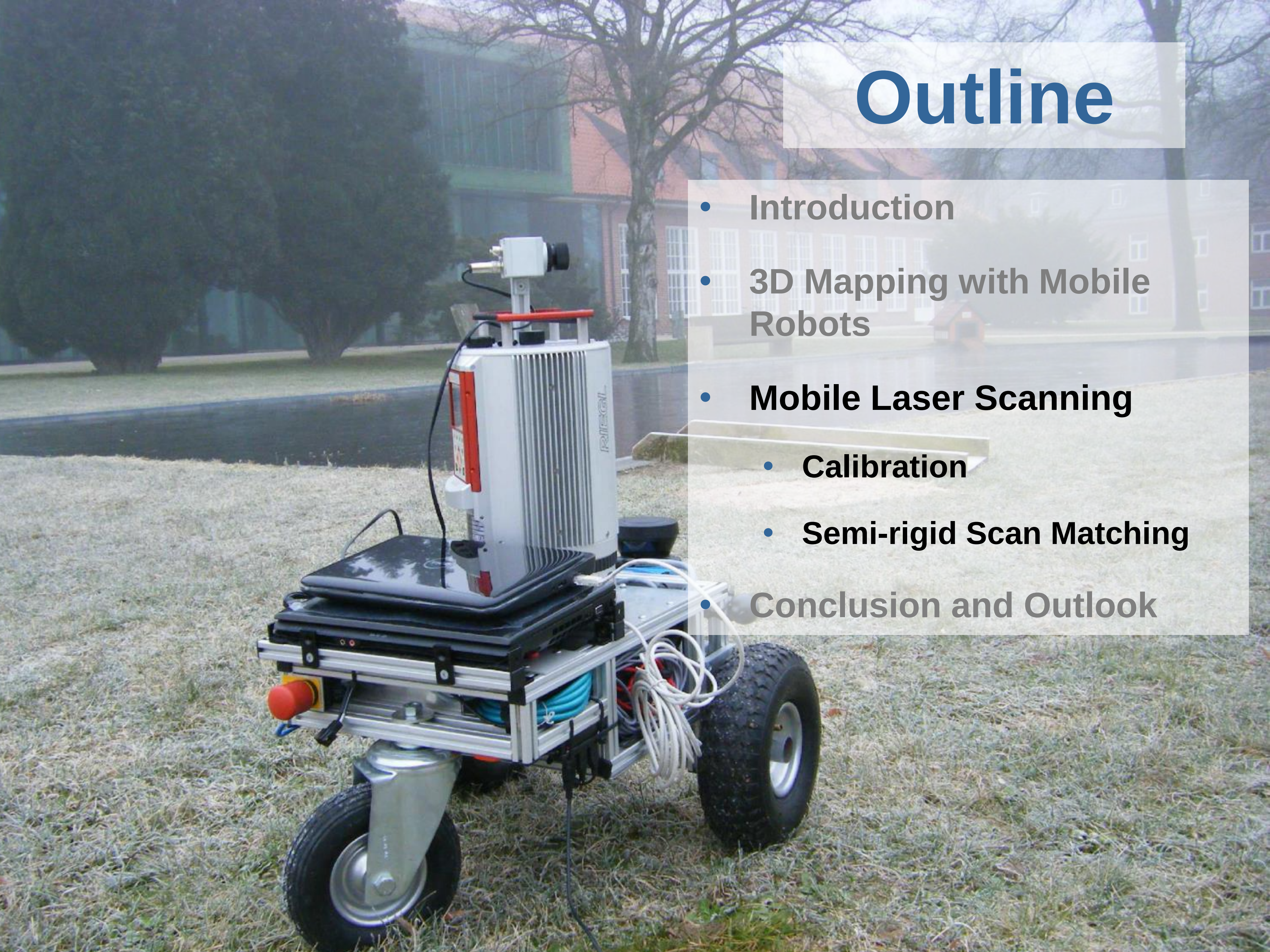
Closed Loop Detection and Global Relaxation



6D SLAM – Full Example

- Leibniz University Hannover (RTS)



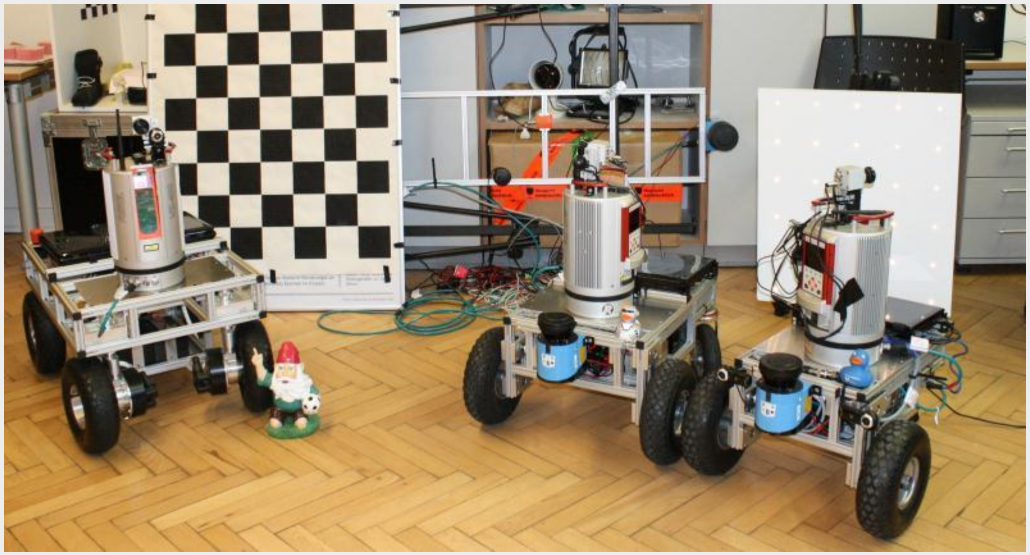


Outline

- Introduction
- 3D Mapping with Mobile Robots
- **Mobile Laser Scanning**
  - **Calibration**
  - **Semi-rigid Scan Matching**
- Conclusion and Outlook

Mobile Laser Scanning Systems

Experimental | Professional



State of the Art

- For all sensors determine the position and orientation on the vehicle (calibration)

- Data Acquisition

- Extract the trajectory of the vehicle from the sensor data (Kalman-Filter)

- “Unwind” the laser measurements with the trajectory to create a 3D point cloud.

Automatic System Calibration

- Construct a calibration vector

$$\mathbf{C} = (a, w, \mathbf{W}_0, o_0, \ldots, \mathbf{W}_n, o_n)$$

- Treat the „unwinding“ as a function $f(M, \mathbf{C})$
- The point cloud represents samples from a probability density function

$$d(\mathbf{l}) = \frac{1}{n} \sum_{j}^{n} G(\mathbf{l} - \mathbf{p}_j, \sigma^2 \mathbf{I})$$

- Simplified entropy measure

$$-\sum_{i}^{n} \sum_{j}^{n} G(\mathbf{p}_i - \mathbf{p}_j, 2\sigma^2 \mathbf{I})$$

Efficient Calibration

- Evaluating the entropy is in $O(n^2)$
- Reduction of the point cloud
  - n becomes smaller
  - Smaller contribution to the error function in the search space
- Reduction of point pairs
  - Consider only pairs with **minimal time difference**
  - Consider only **closest points**
- Minimization of the error function

$$\hat{\mathbf{C}} = \underset{\mathbf{C}}{\operatorname{argmax}}\, E(f(M, \mathbf{C}))$$

where $E(f(M, \mathbf{C})) = -\sum_{i}^{n} G(\mathbf{p}_i - \mathbf{q}_i, 2\sigma^2 \mathbf{I})$

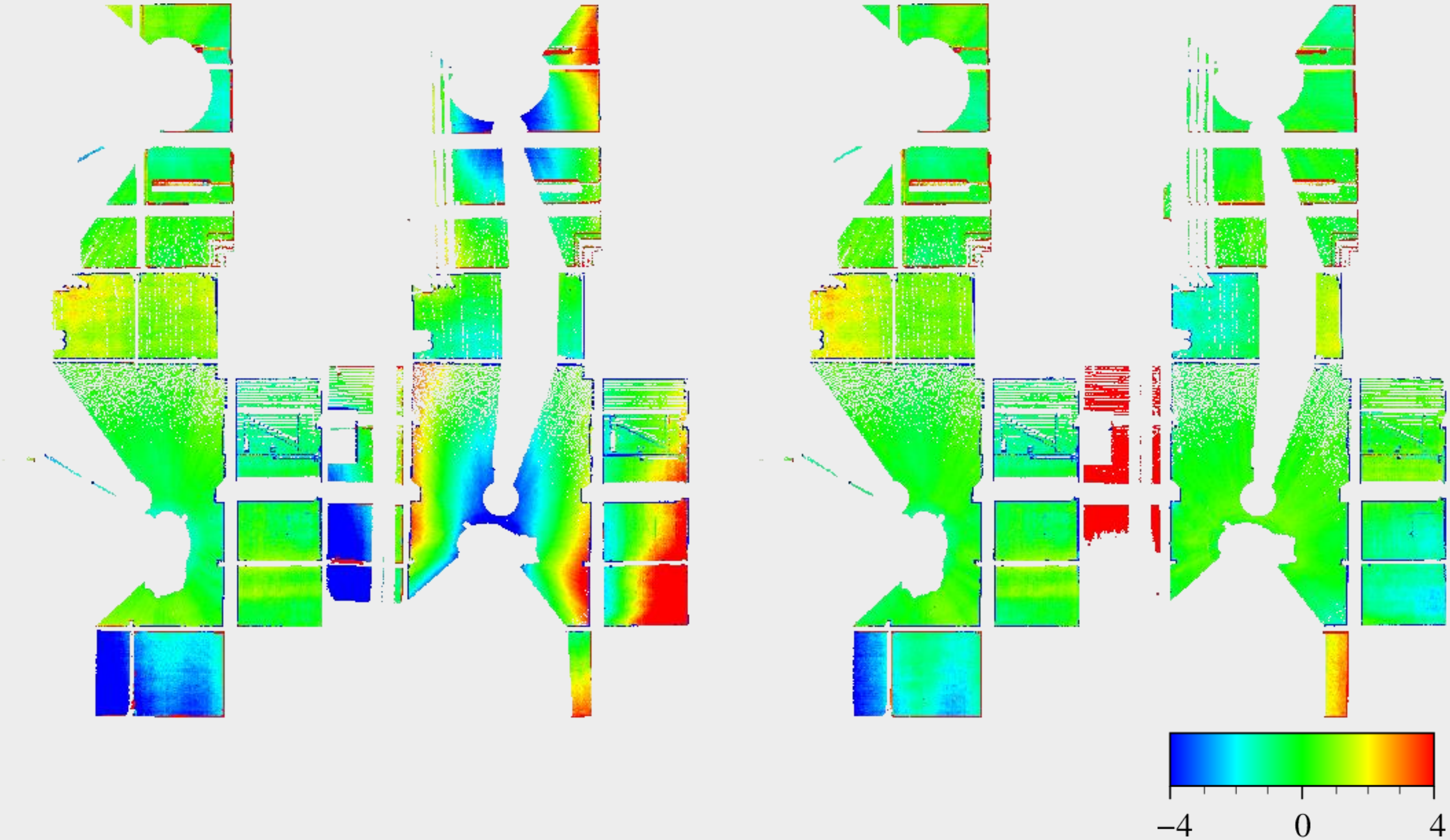
is in O(n log n)   (~20 minutes with Powel's algorithm)

Calibration Experiment (1)



- Reference model: 3D plane model from terrestrial scanning
- Compare point cloud with model

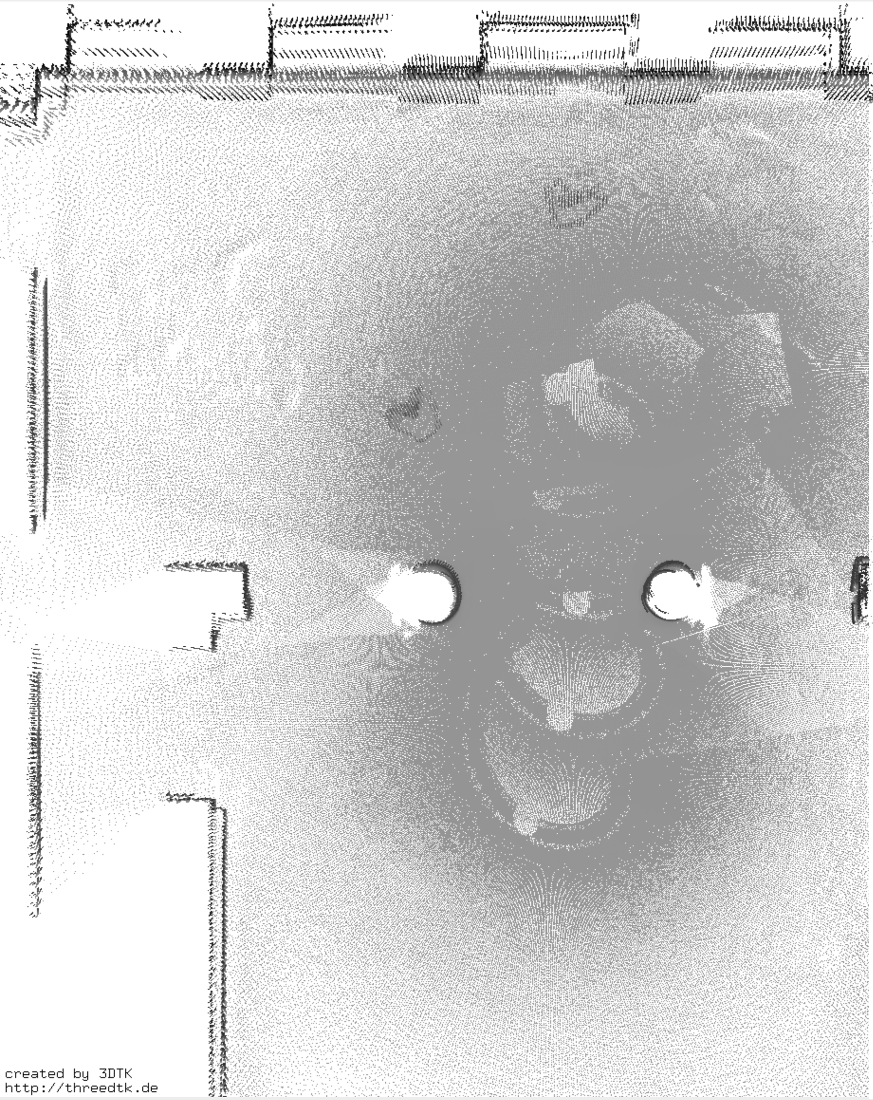
Calibration Experiment (1)

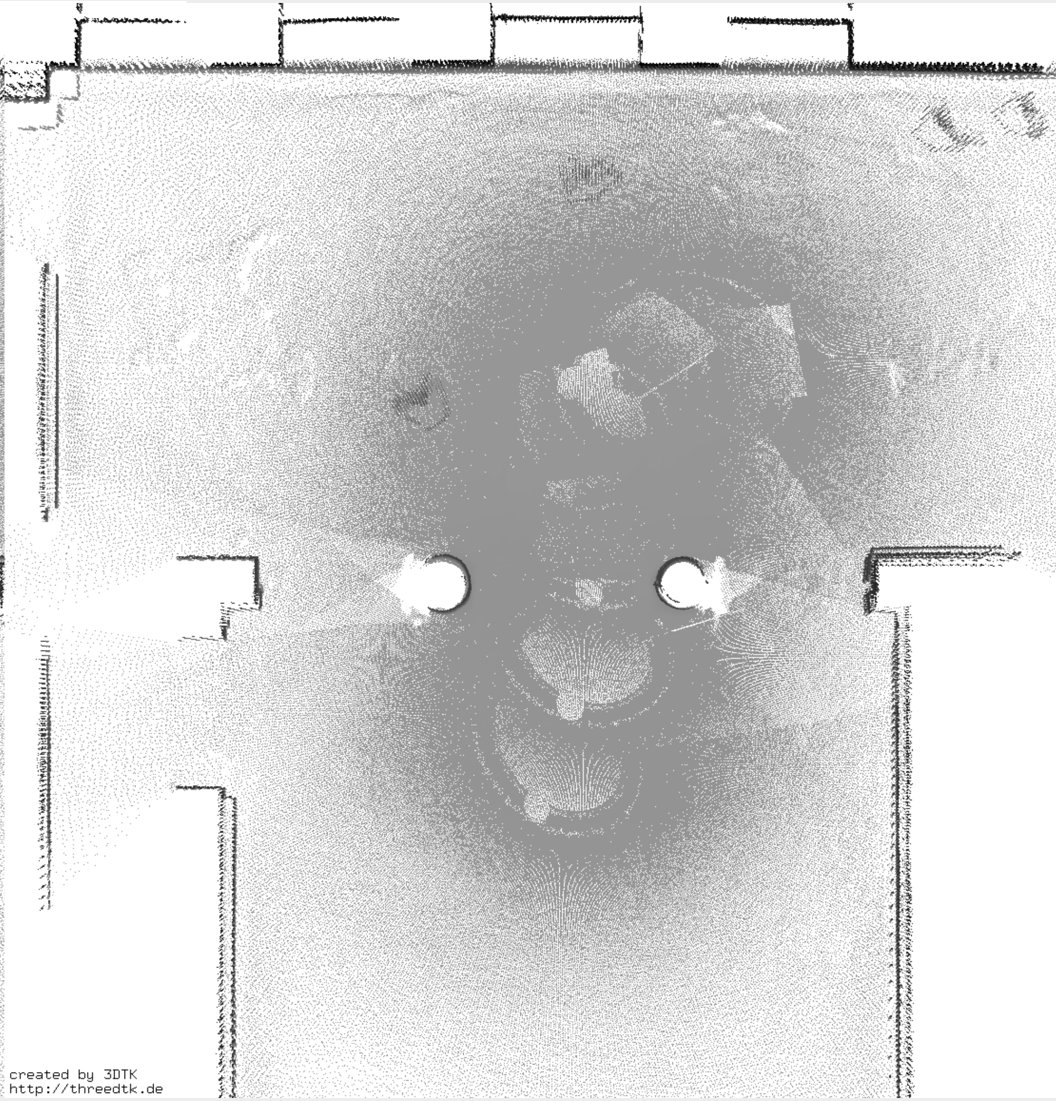


Calibration Experiment (2)

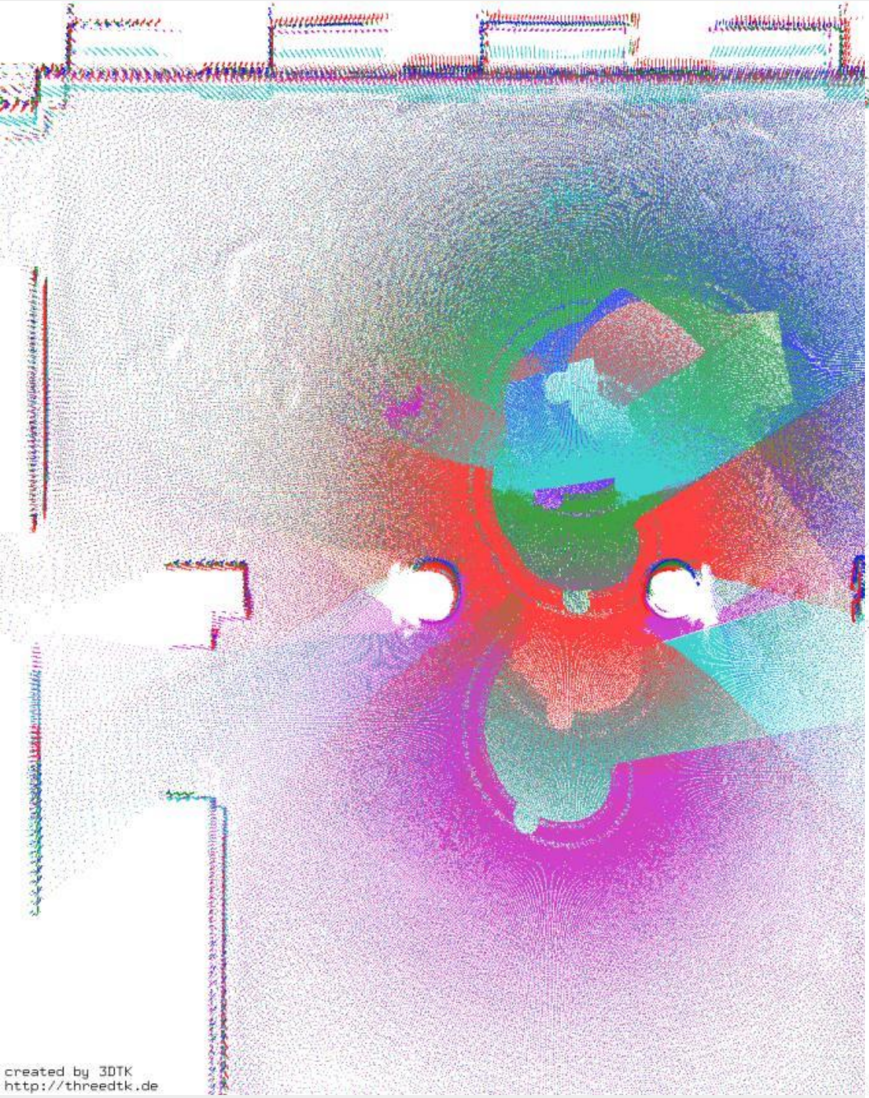
- Ostia Antica in Rom
- Environment less structured
- No ground truth model available

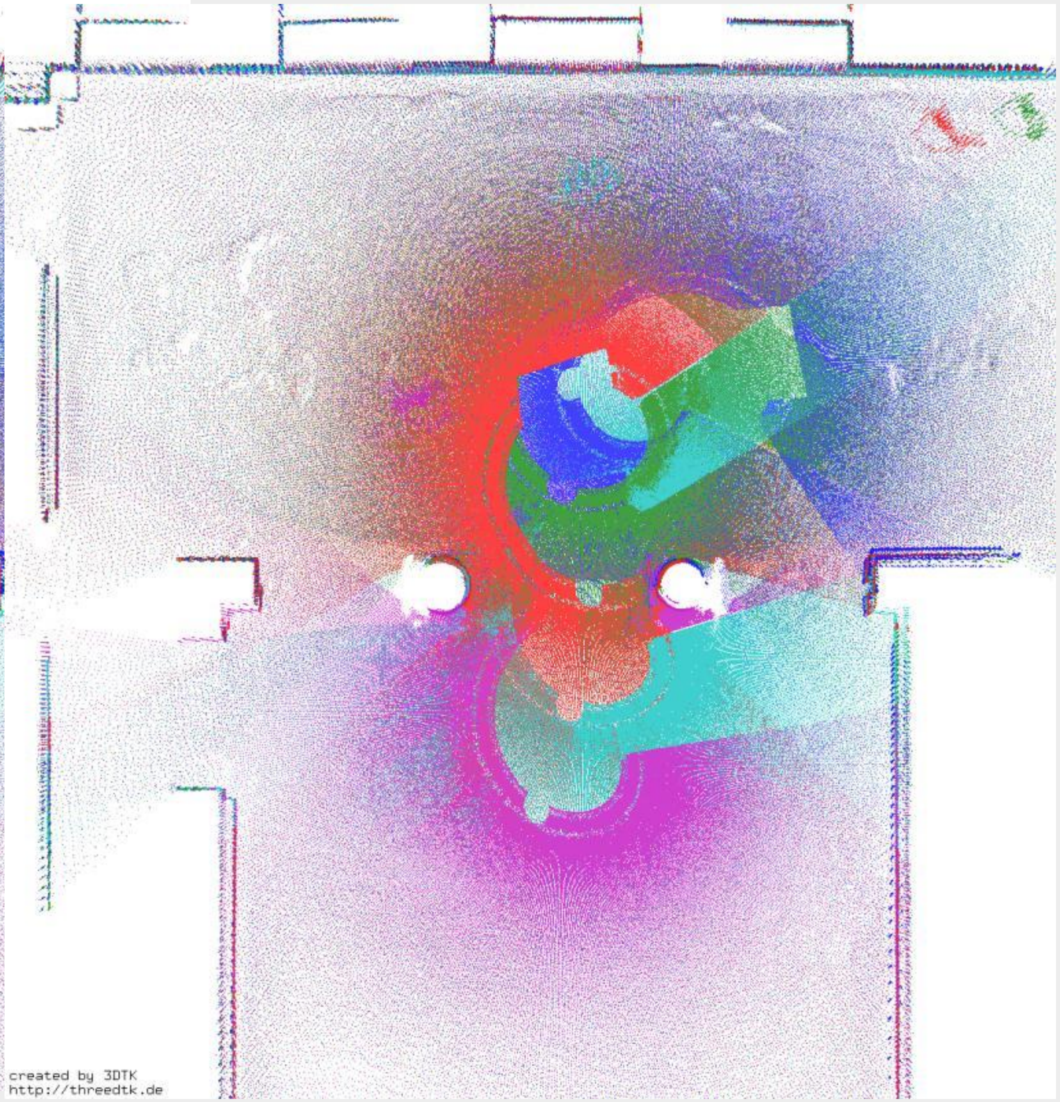
Calibration Experiment (2)



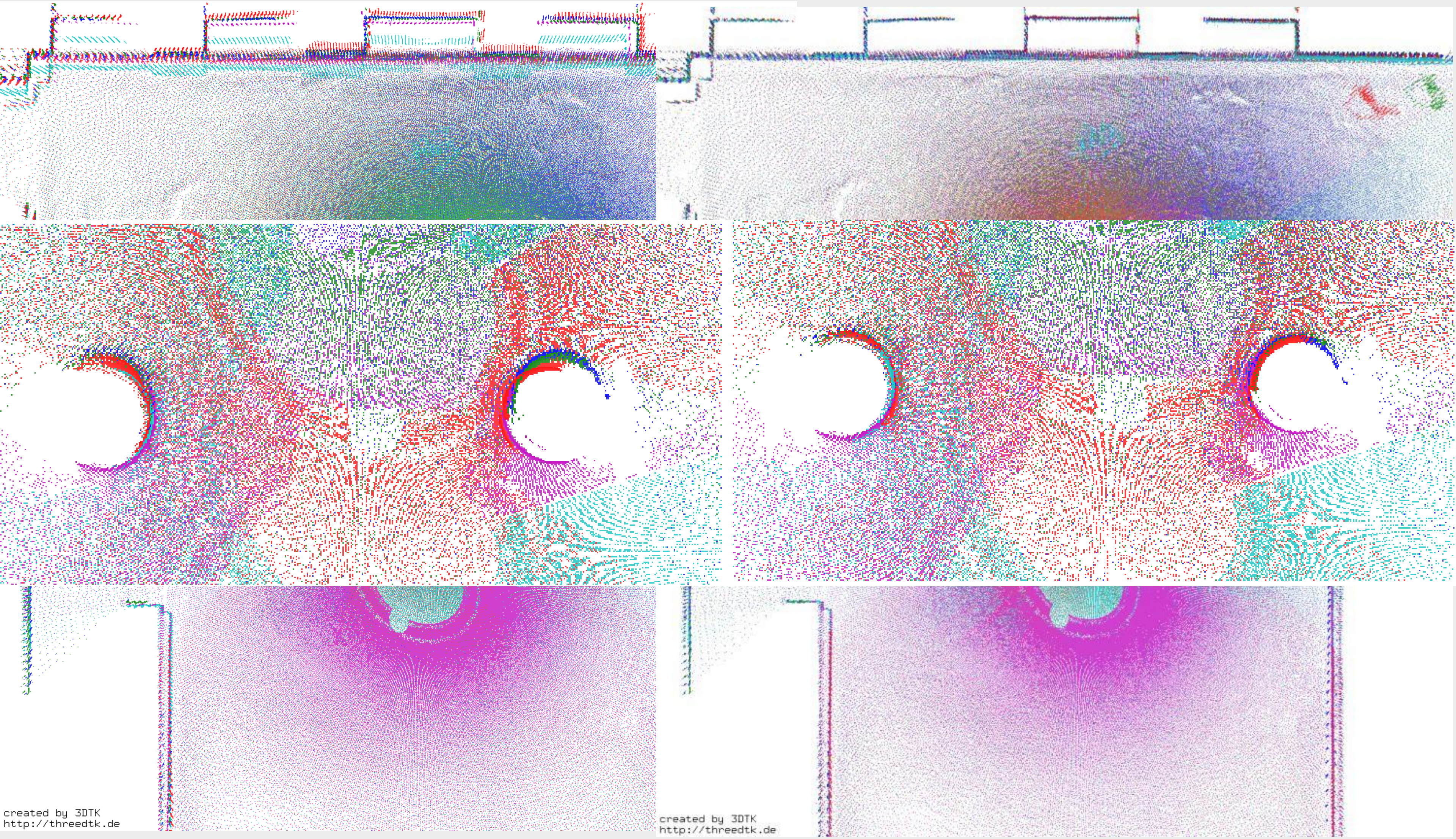


Calibration Experiment (2)





Calibration Experiment (2)



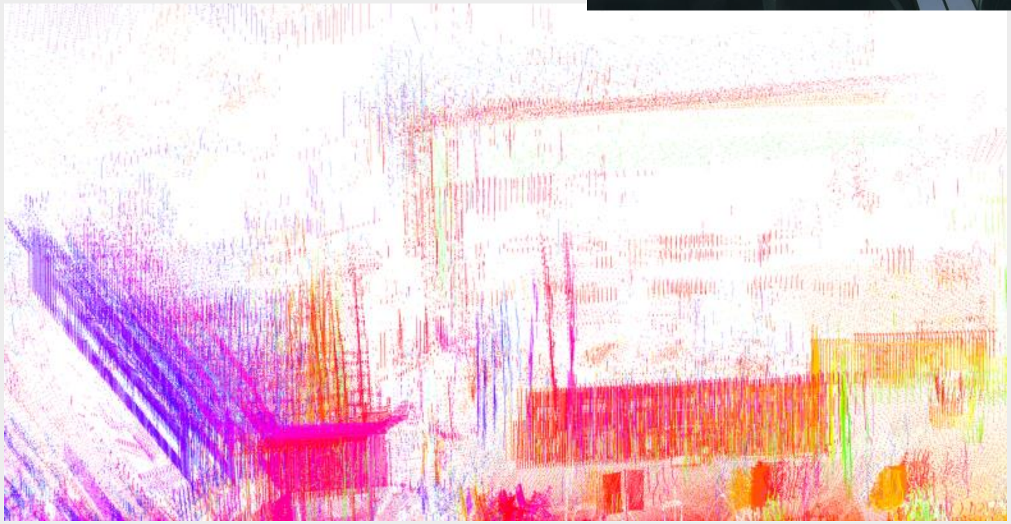
Further Sources of Errors

no GPS

„lousy“ IMU

bad GPS

no IMU



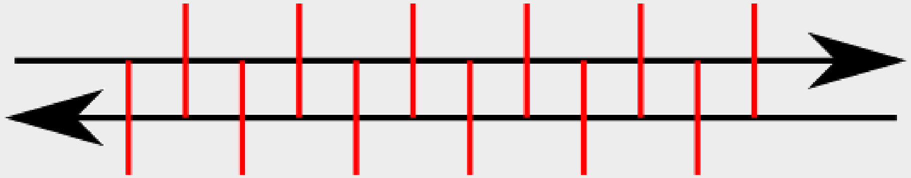
Semi-Rigid Registration

- Goal:
  - Optimize trajectory
  - No or only small time discretization (< 10 ms)
  - Ideal discretization at every point measurement
- Ansatz:
  - Extension of the global ICP algorithm / Graph-SLAM
- Modeling
  - Trajectory $T = \{\mathbf{V}_0, \ldots, \mathbf{V}_n\}$
  - Every $\mathbf{V}_i$ is a vehicle pose at time t_i
  - IMU / odometry estimate $\mathbf{V}_i \to \mathbf{V}_{i+1}$
  - GPS estimate $\mathbf{V}_0 \to \mathbf{V}_i$
  - Laser scanner / scan matching $\mathbf{V}_i \to \mathbf{V}_j$

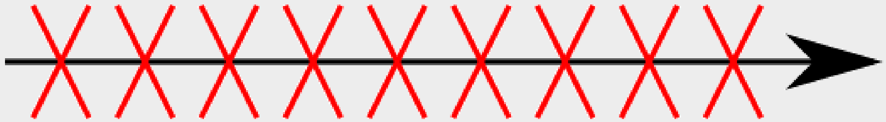
Calculation of $\mathbf{V}_i \rightarrow \mathbf{V}_j$

- "Unwind" the laser measurements with the trajectory to create an initial 3D point cloud.
- Compute correspondences using a modified nearest-neighbor search
- Consider the following scenarios:

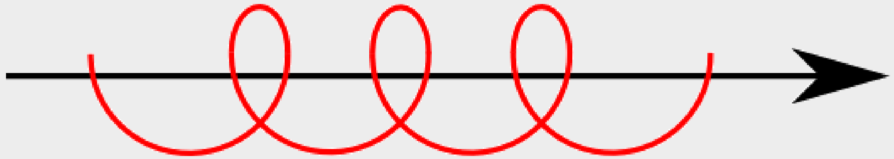
1 2D scanner



2 2D scanners



1 rot. 3D scanner



Optimization of the Trajectory

- Global error function

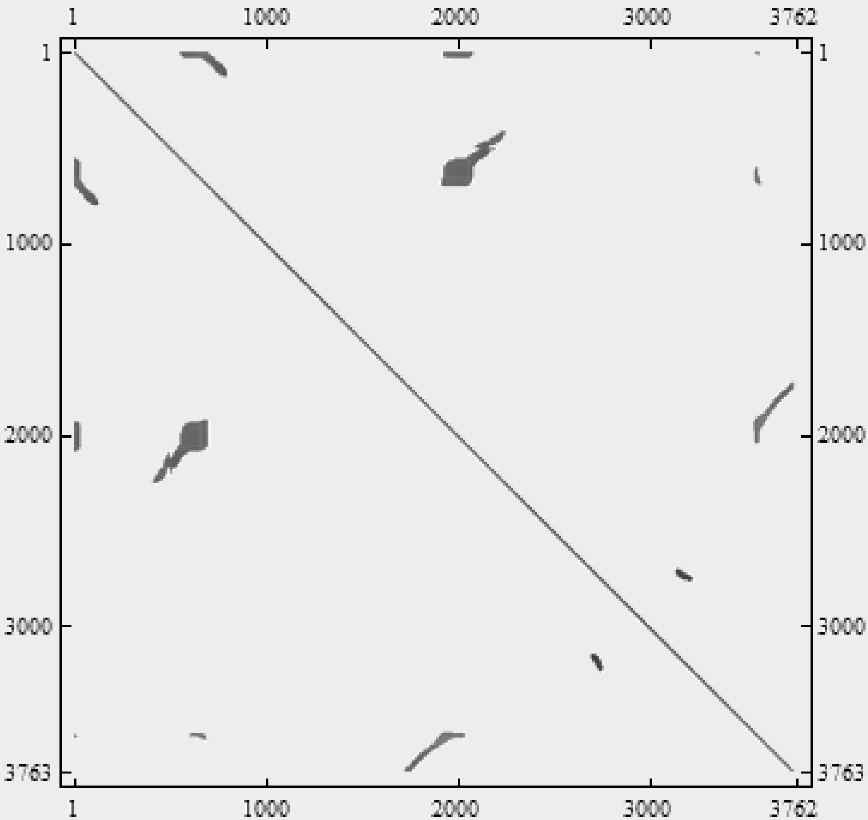
$$W = \sum_i \sum_j (\bar{\mathbf{V}}_{i,j} - (\mathbf{V}'_i - \mathbf{V}'_j))\mathbf{C}_{i,j}^{-1}(\bar{\mathbf{V}}_{i,j} - (\mathbf{V}'_i - \mathbf{V}'_j))$$

- Minimization by

$$(\mathbf{H}^T\mathbf{C}^{-1}\mathbf{H})\mathbf{V} = \mathbf{H}^T\mathbf{C}^{-1}\bar{\mathbf{V}}$$

- Solving by Sparse Cholesky Decomposition by T. Davis

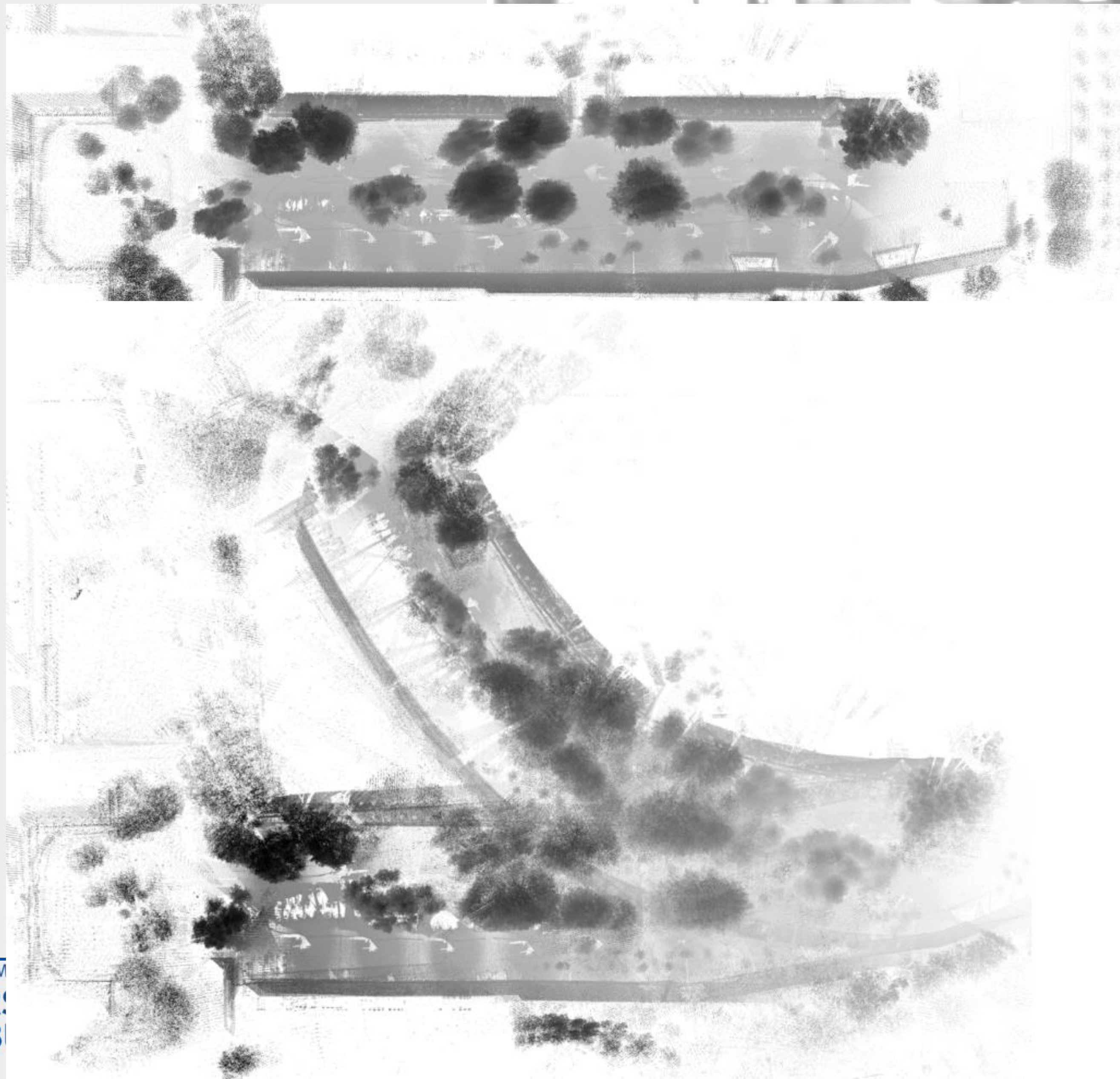
- Also possible: global ICP



Overview: Algorithm Semi-Rigid SLAM

1. Calculate the pose estimates
   $\mathbf{V}_i \rightarrow \mathbf{V}_{i+1}$ and $\mathbf{V}_0 \rightarrow \mathbf{V}_i$
2. Extract a 3D point cloud from a current trajectory estimate and the system calibration
3. Calculate an oc-tree for storing the 3D points (including the time stamp)
4. Compute closest points and an estimate for
   $\mathbf{V}_i \rightarrow \mathbf{V}_j$
5. Update the trajectory
6. Repeat step 2 – 5 until convergence

Experiment I

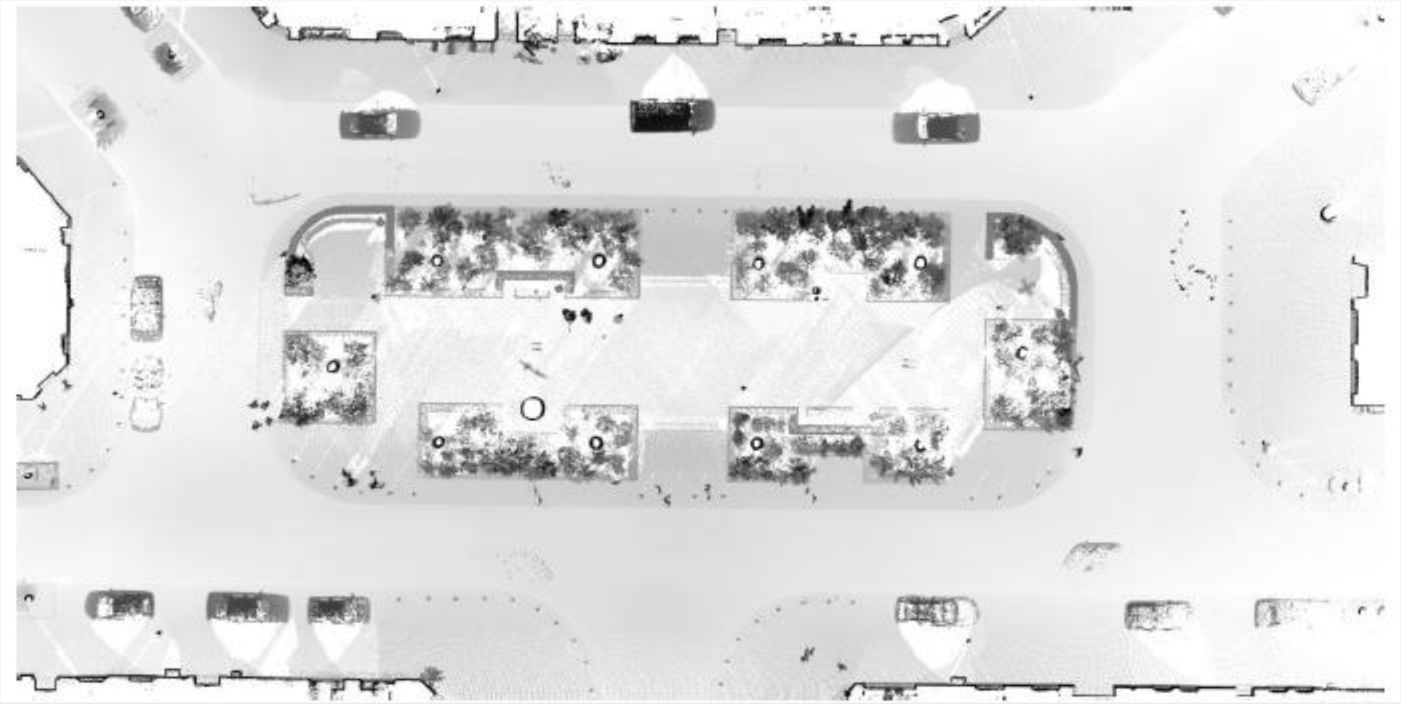


Experiment II

- Data and analysis done by TopScan GmbH, Rheine (Dr. Joachim Lindenberger)

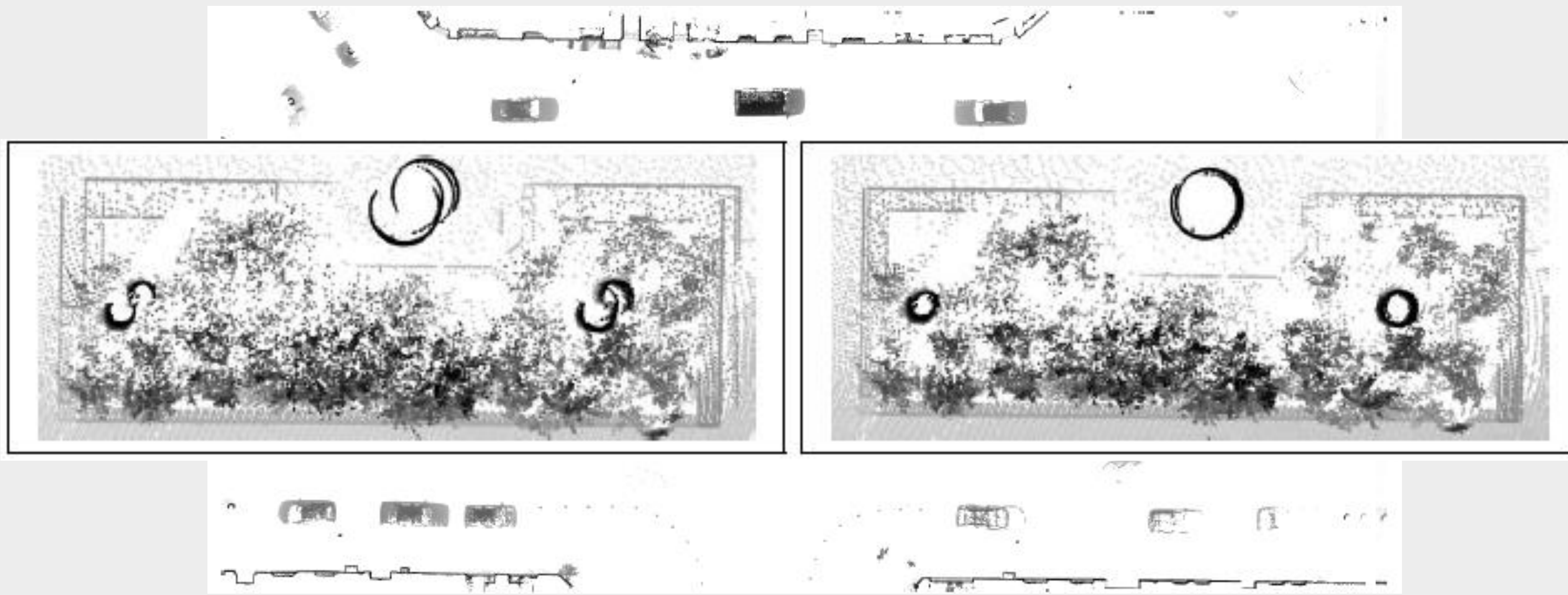
Experiment II

- Data and analysis done by TopScan GmbH, Rheine (Dr. Joachim Lindenberger)

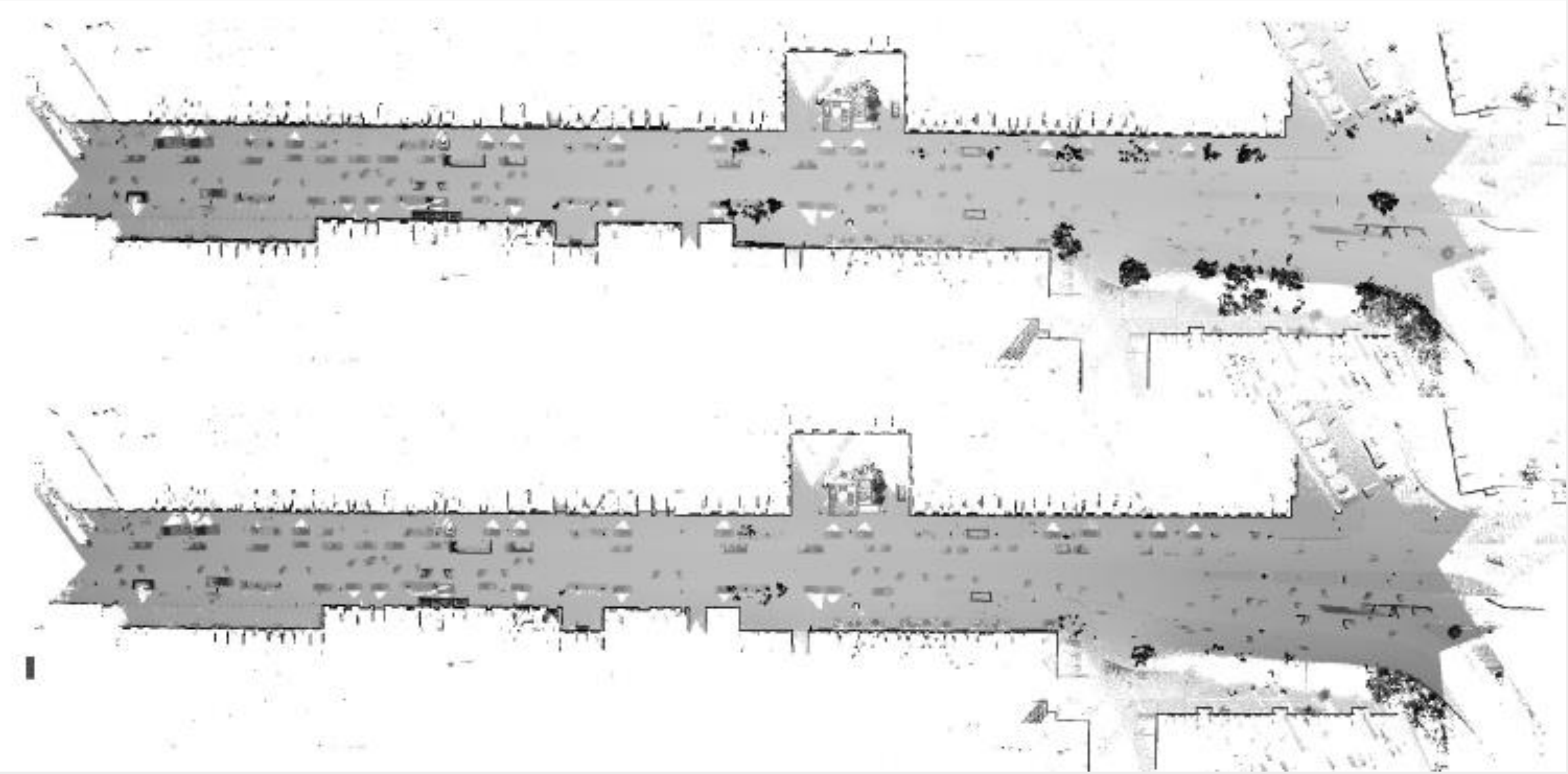


Experiment II

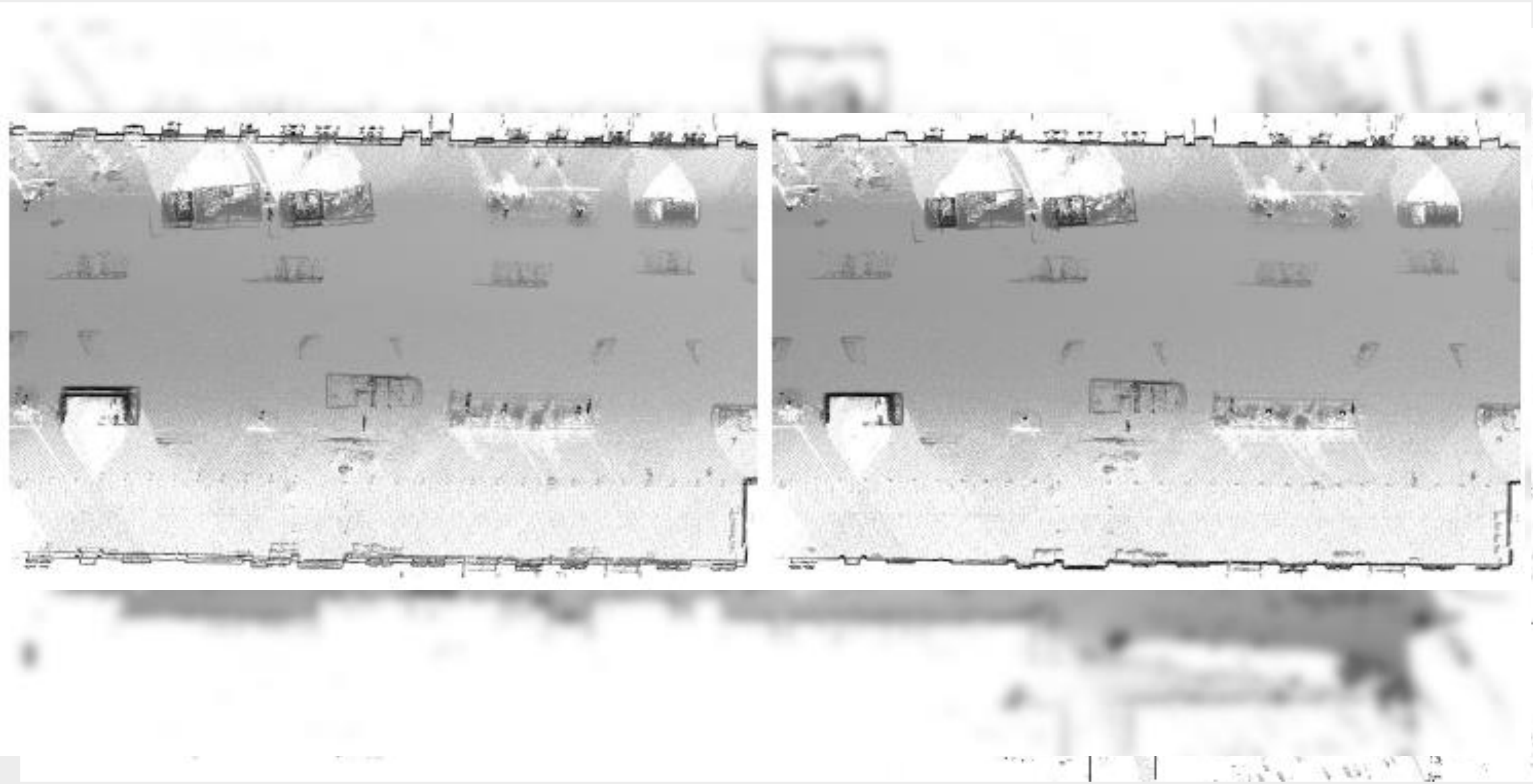
- Data and analysis done by TopScan GmbH, Rheine (Dr. Joachim Lindenberger)



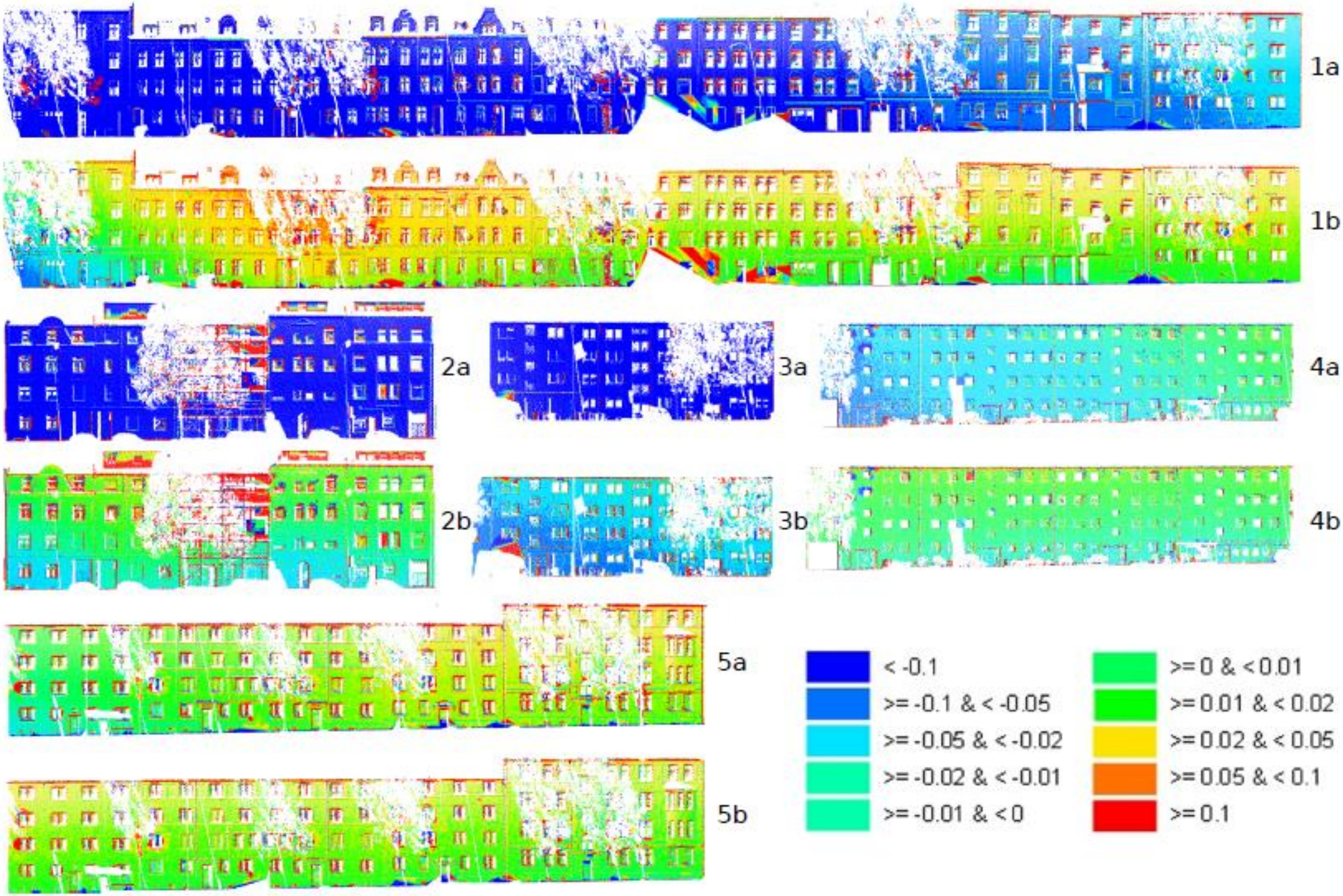
Experiment II



Experiment II



Experiment II



Experiment III

Experiment III

- Acquired by Riegl GmbH in Salzburg

Experiment III

- Acquired by Riegl GmbH in Salzburg

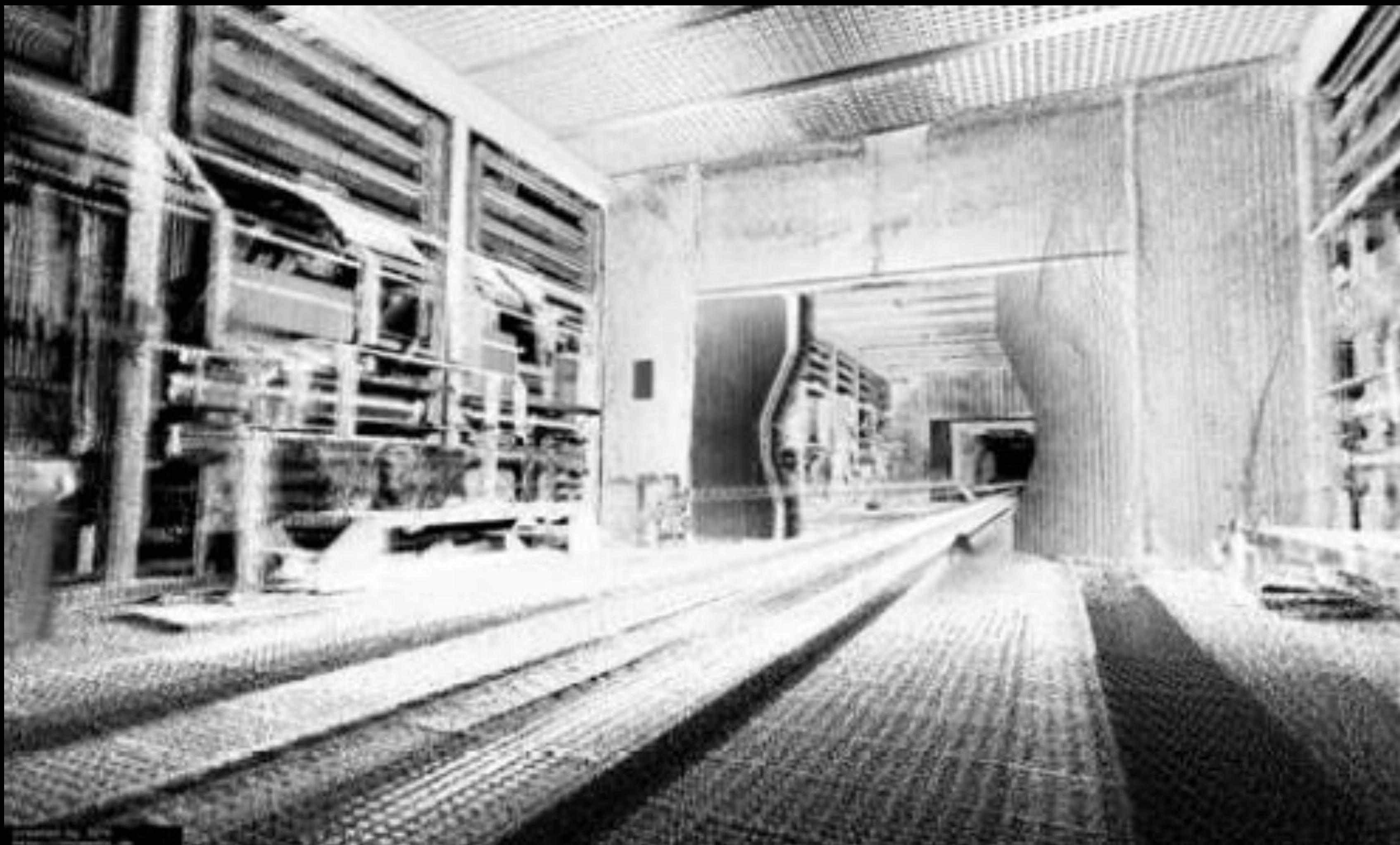
Outline

- Introduction
- 3D Mapping with Mobile Robots
- Mobile Laser Scanning
  - Calibration
  - Semi-rigid Scan Matching
- **Conclusion and Outlook**

Summary and Outlook

- Efficient algorithms and data structures for processing 3D point clouds
- Golbal consistent scan matching
  - ⇨ Bundle Adjustment for 3D Point Clouds
  - ⇨ “Dense“ method

Application: 3D Point Clouds at the Production Line



References

- Publications available at

  www.nuechti.de

- Videos are online on our youtube channel

  www.youtube.com/channel/UC7HAqZXI-jvMmBwoi4vDUew

  www.youtube.com/user/AutomationAtJacobs

  www.youtube.com/user/AndreasNuechter

- Large parts of our software is Open Source

  3DTK – The 3D Toolkit

  http://slam6d.sourceforge.net