6D SLAM with Cached kd-tree Search

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Joint work with Kai Lingemann, Joachim Hertzberg

This talk is about 3D mapping using six degree of freedom.

Contents

- **State of the Art in Robotic Mapping**
- **6D SLAM with Scan Matching**
- **Approximate and Exact Data Association**
- **3D Mapping Examples**

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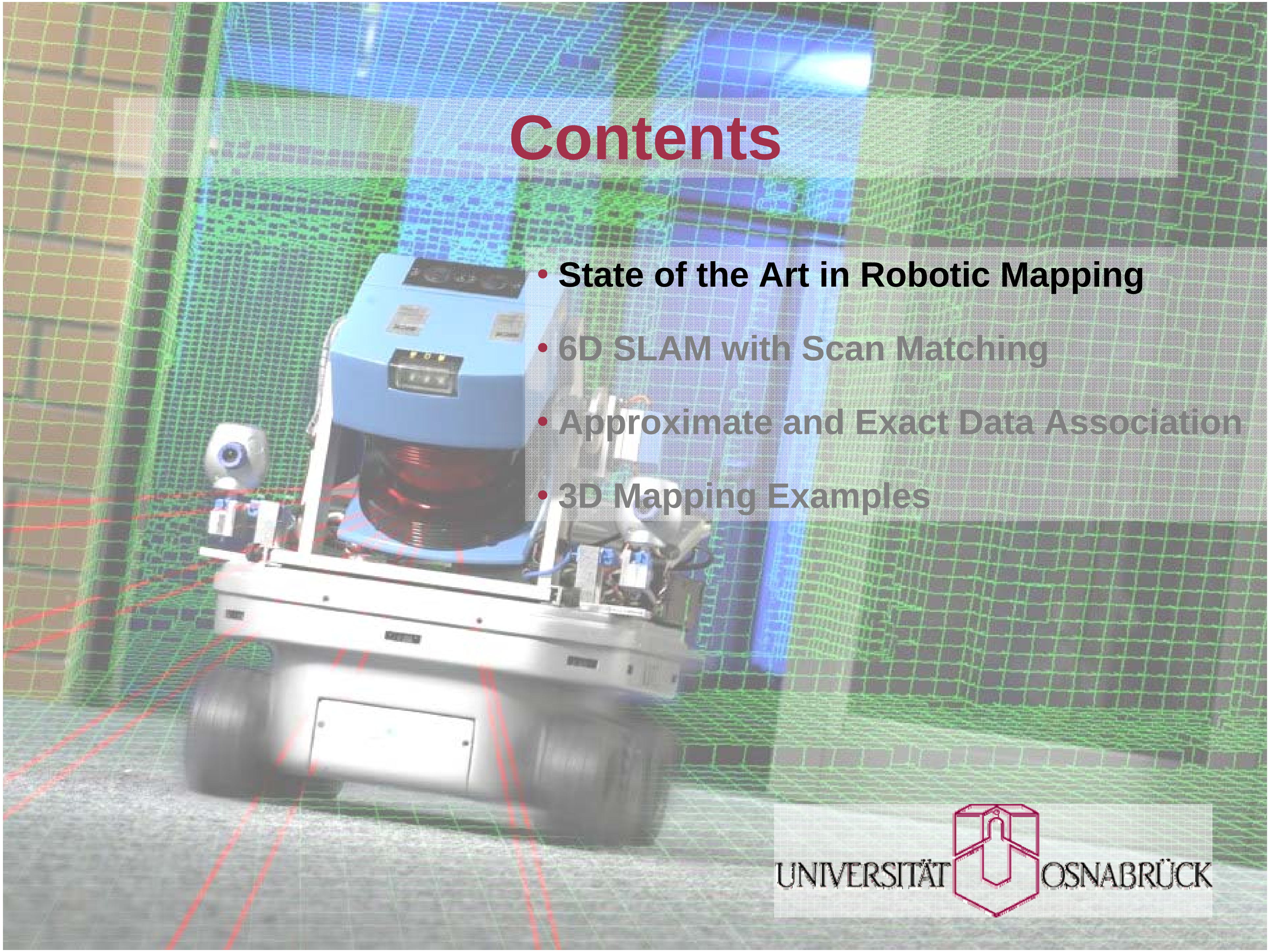

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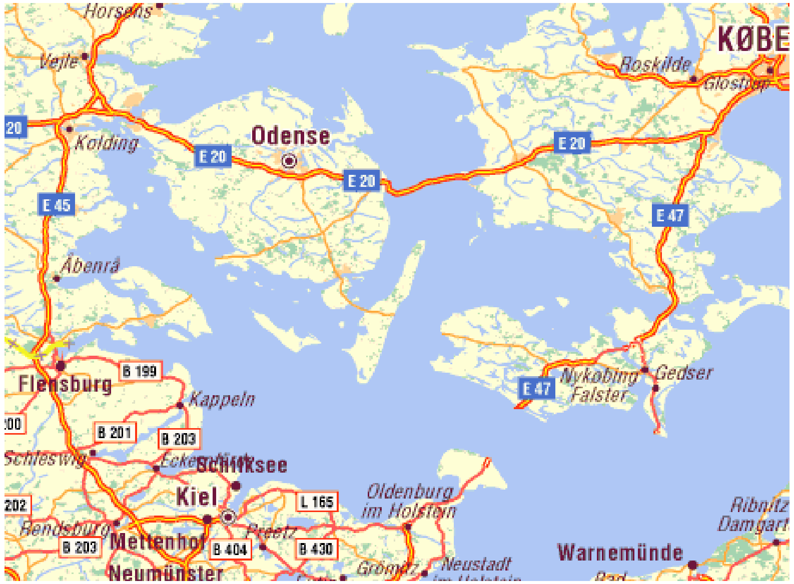
Simultaneous Localization and Mapping

- If one knows the pose (position and orientation) of a mobile robot precisely, then the sensor readings can be used to build a map.
- Unfortunately, pose measurements are always imprecise ☹
- The pose of a robot is easy to compute from sensor readings, given a map.



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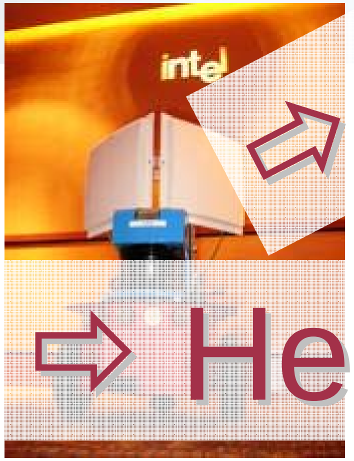
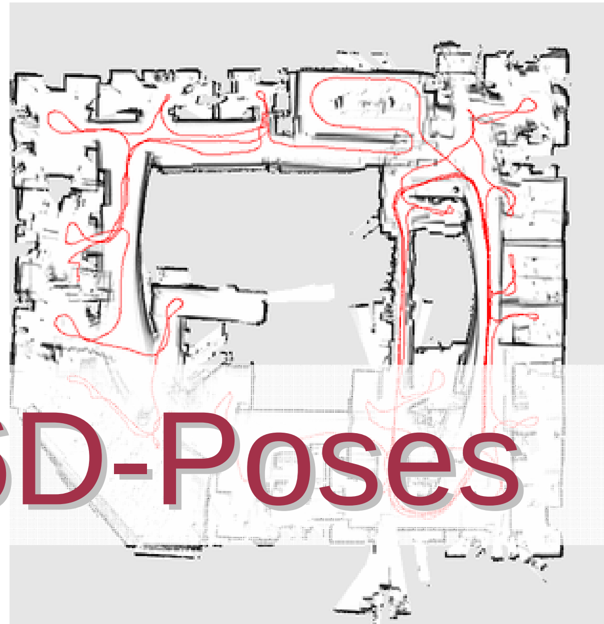
State of the Art in Robotic Mapping (1)

- Laser scanner are the state of the art sensors for metrical environment mapping
- Mapping based on scan matching (Lu, Milios)
- Probabilistic theory of mapping using uncertain motion and sensor models (Kalman-Filter, Maximum Likelihood Estimation, Expactation Maximation).



⇨ 2D-Data, 3D-Poses



⇨ Here: 3D-Data, 6D-Poses

Related work: Freiburg (Burgard),
UW (Fox),
Stanford (Thrun)

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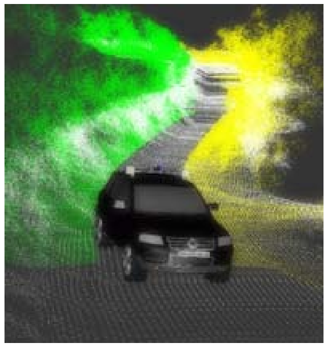
State of the Art in Robotic Mapping (2)

		Dimensionality of pose representation	
		3D	6D
Sensor data	2D		
	3D		






The Mobile Robot Kurt3D

- Kurt3D is a leightweight (25 kg)
- Two 90W (200W) motors, 48 NiMH a 4500mAh, C167 Microcontroller, CAN Controller, Centrino Notebook

- Indoor/Outdoor versions available
- main Sensor: 3D scanner ⇨ 3D data, 6D poses

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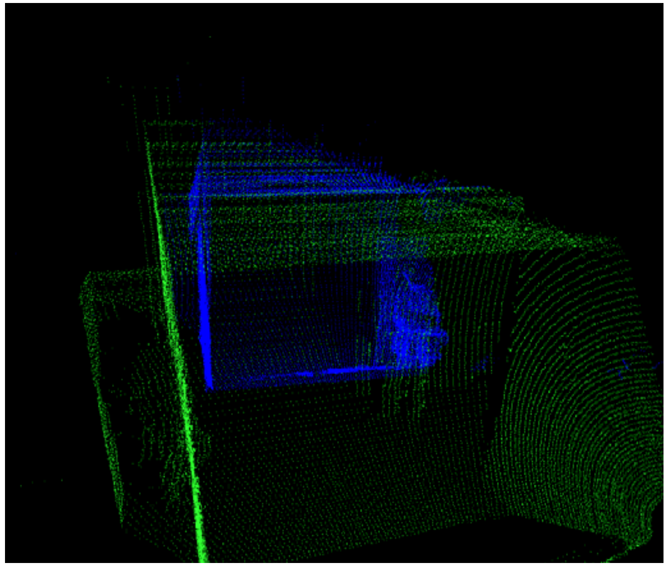
The ICP-Algorithm

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 $w_{i,j}$ in {0,1}
2. Minimize for rotation $\mathbf{R}$, translation $\mathbf{t}$

$$E(\mathbf{R},\mathbf{t}) = \sum_{i=1}^{N_m} \sum_{j=1}^{N_d} w_{i,j} \, ||\mathbf{m}_i - (\mathbf{R}\mathbf{d}_j + \mathbf{t})||^2$$

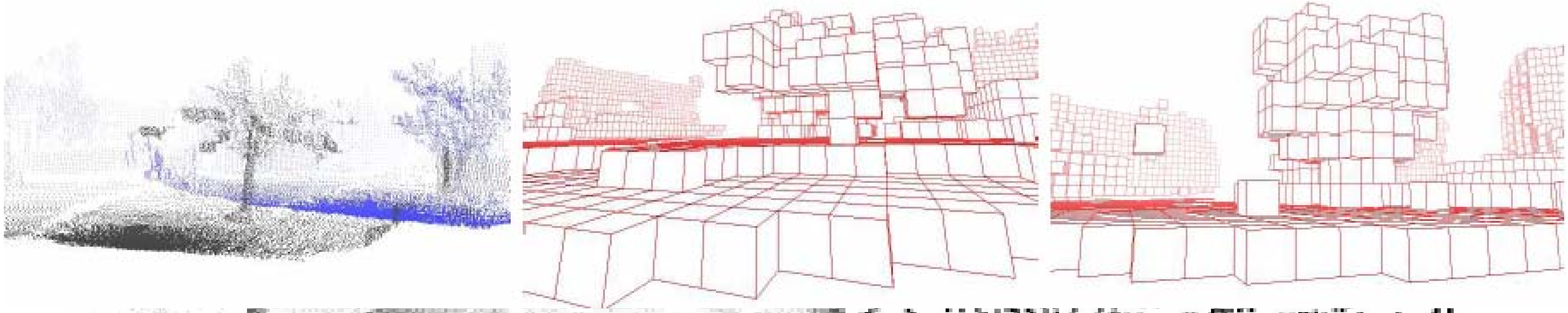
3. Iterate **1.** and **2.**

SVD-based calculation of rotation

- works in 3 translation plus 3 rotation dimensions
  ⇒ 6D SLAM with closed loop detection and global relaxation.

6D SLAM Algorithm Overview

1. Find a heuristic pose update using octrees [KI 2005].



t)

Note: Results are already quite good at this points.

4. Global relaxation.

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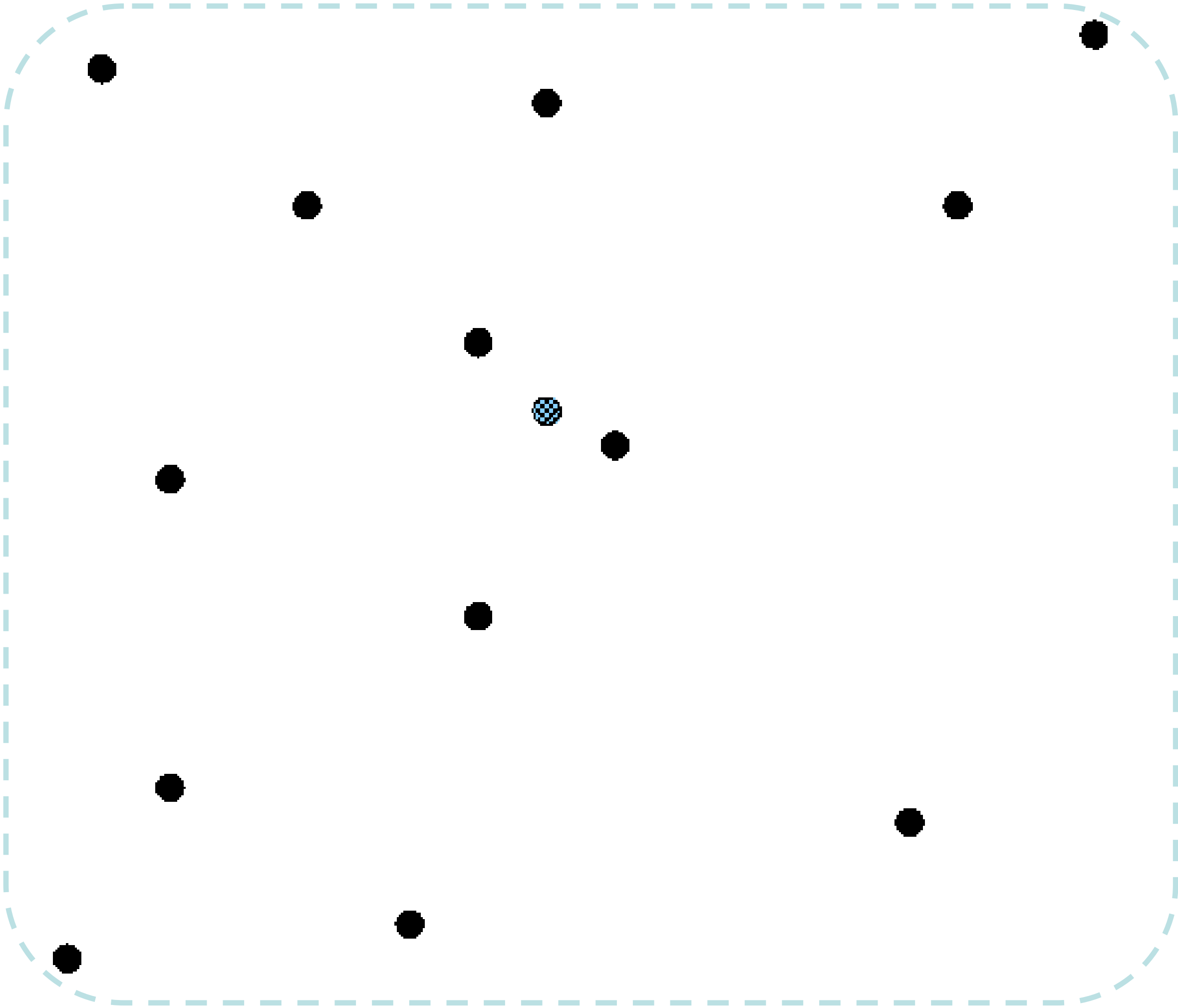
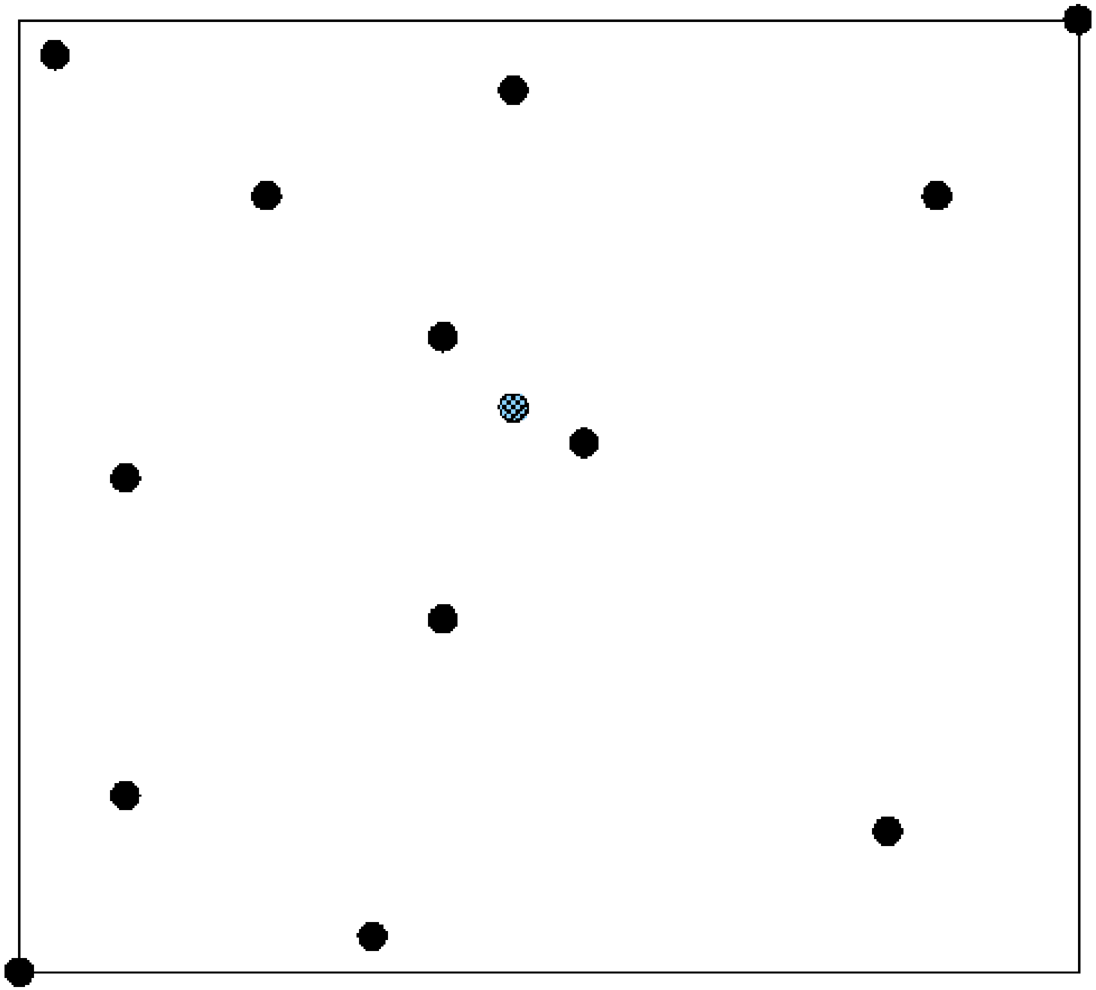
Nearest Neighbor Search

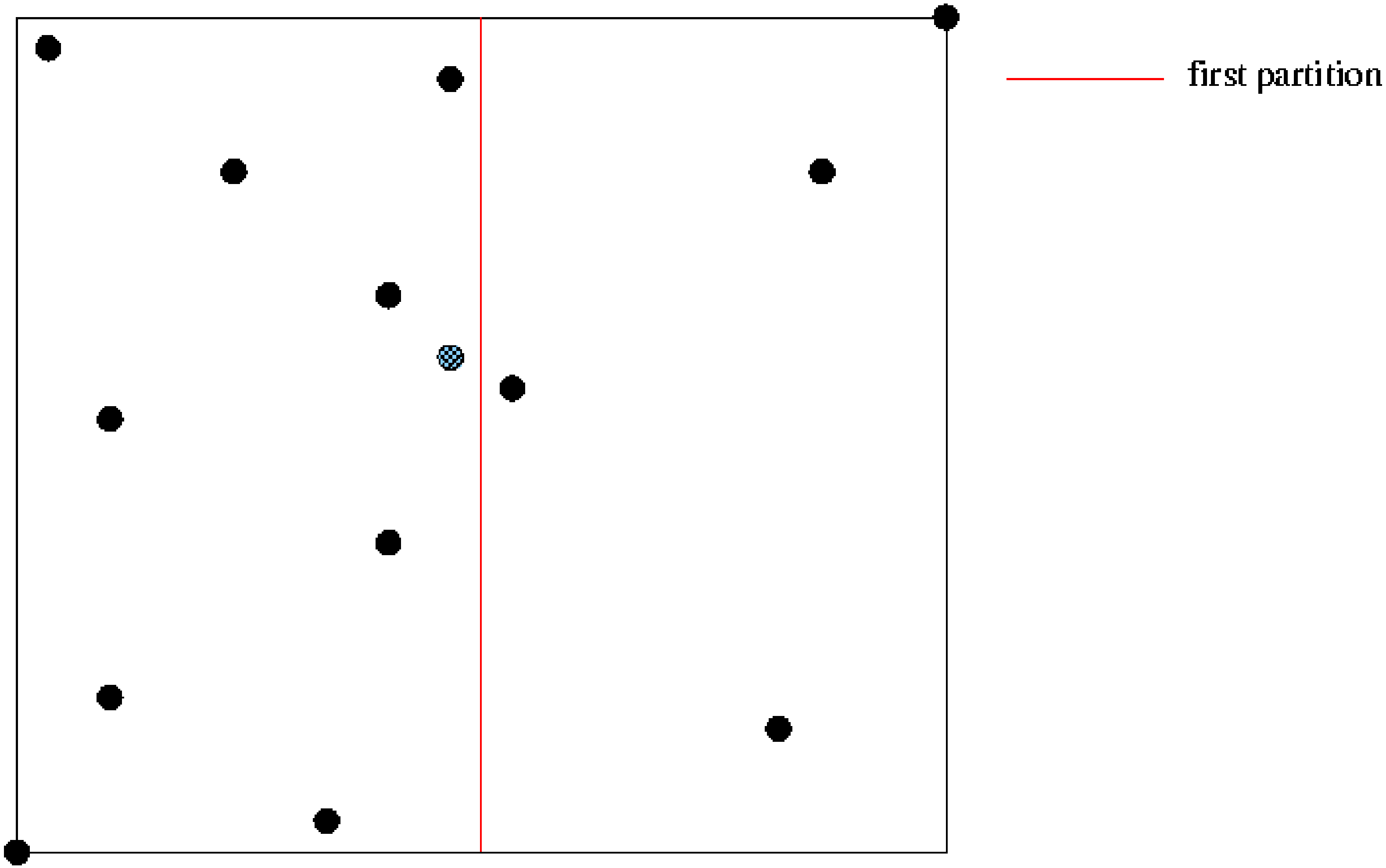


- Given: Set of points.
- Building *k*D-tree for implementing a fast search, **log *n*** time
- Idea: Recursively splitting the region into two equal partitions.

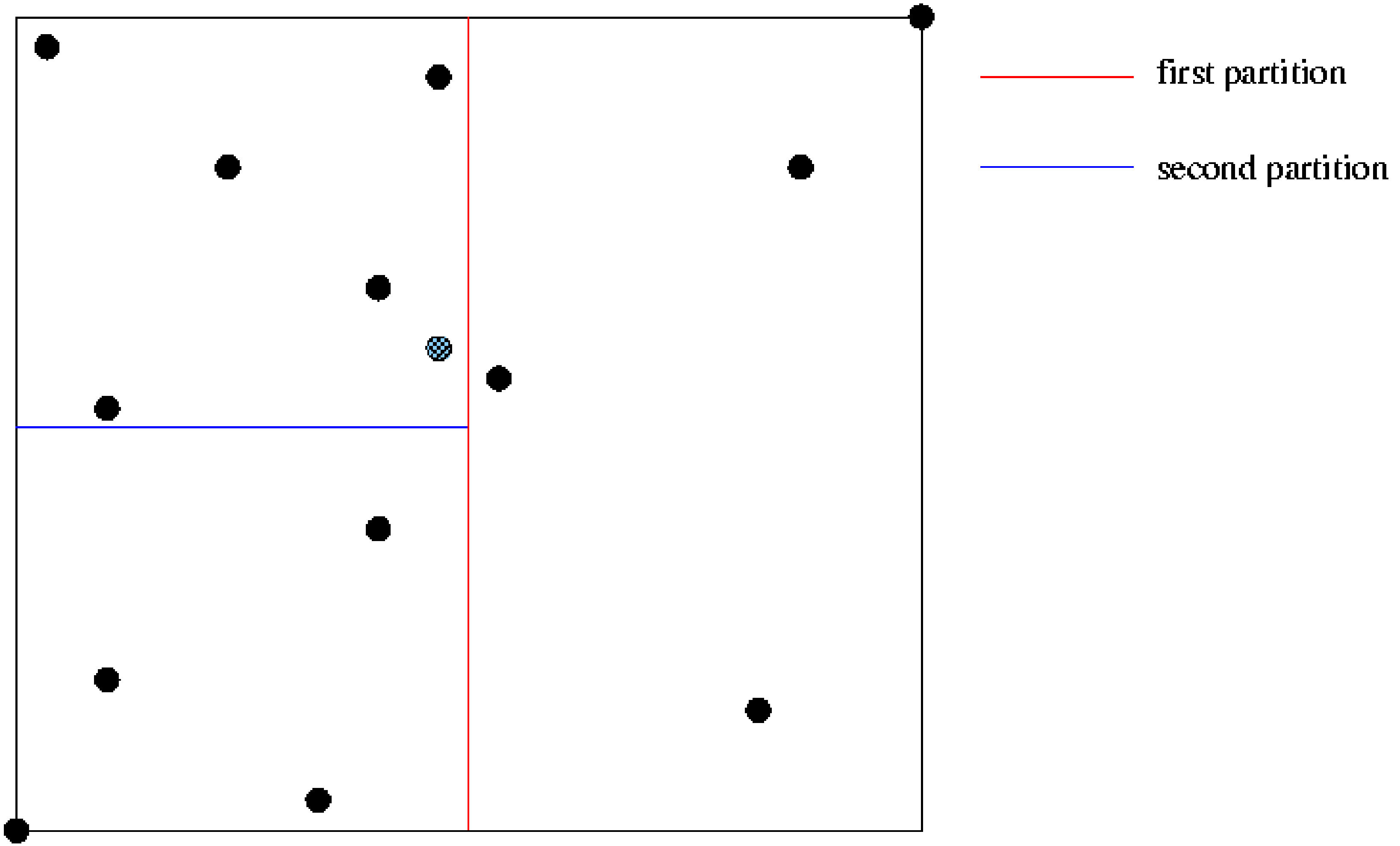
Nearest Neighbor Search



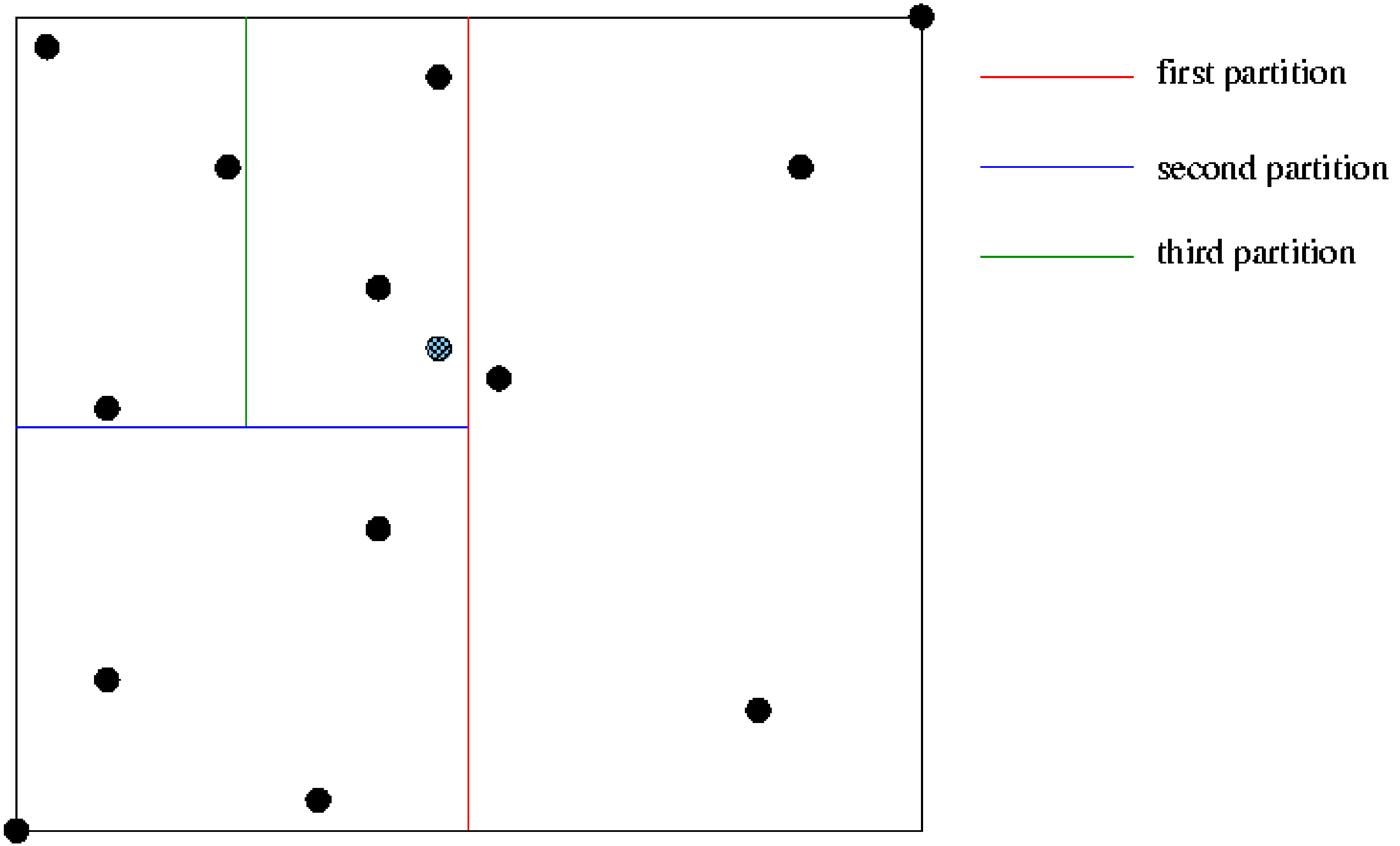
Nearest Neighbor Search



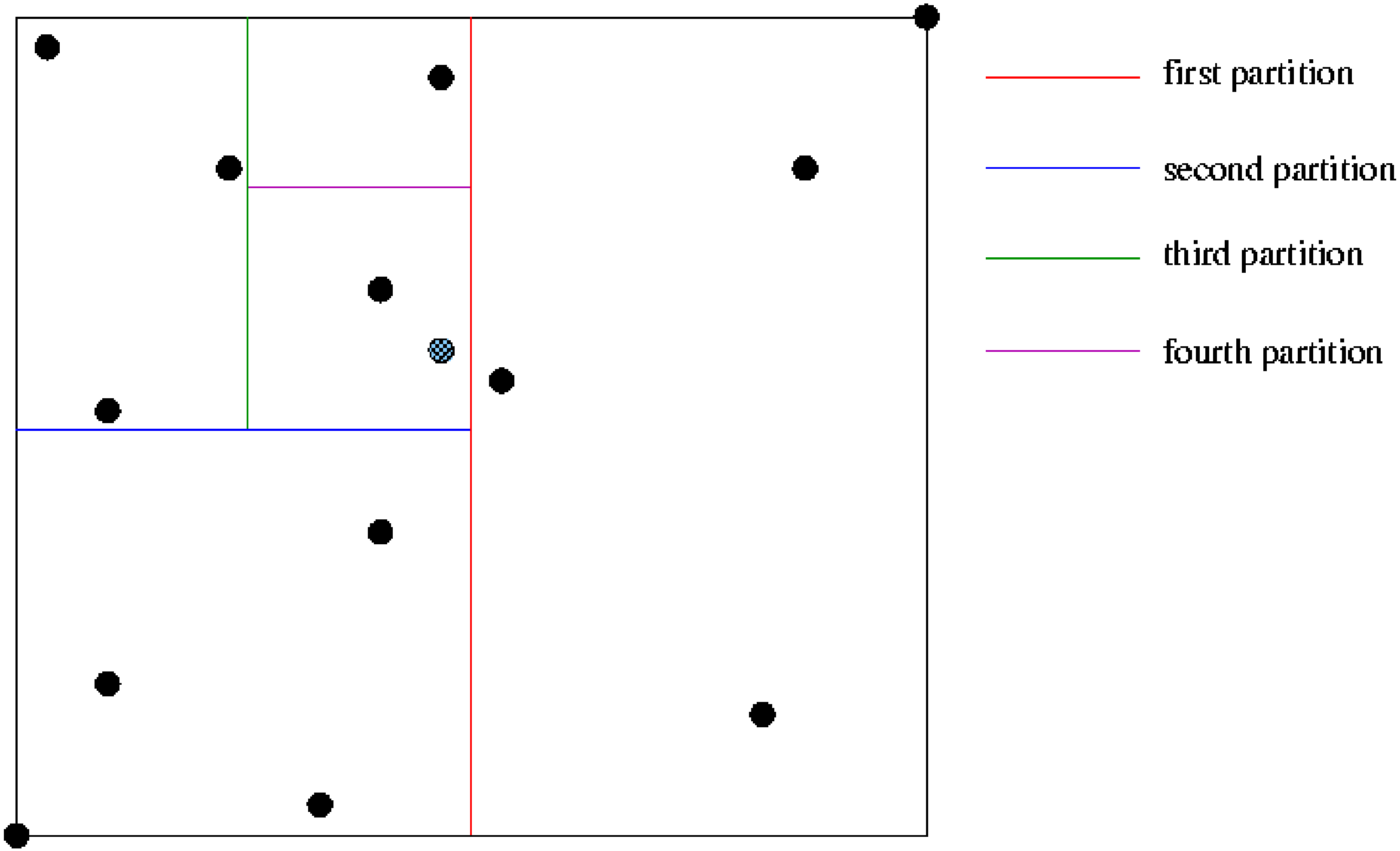
Nearest Neighbor Search



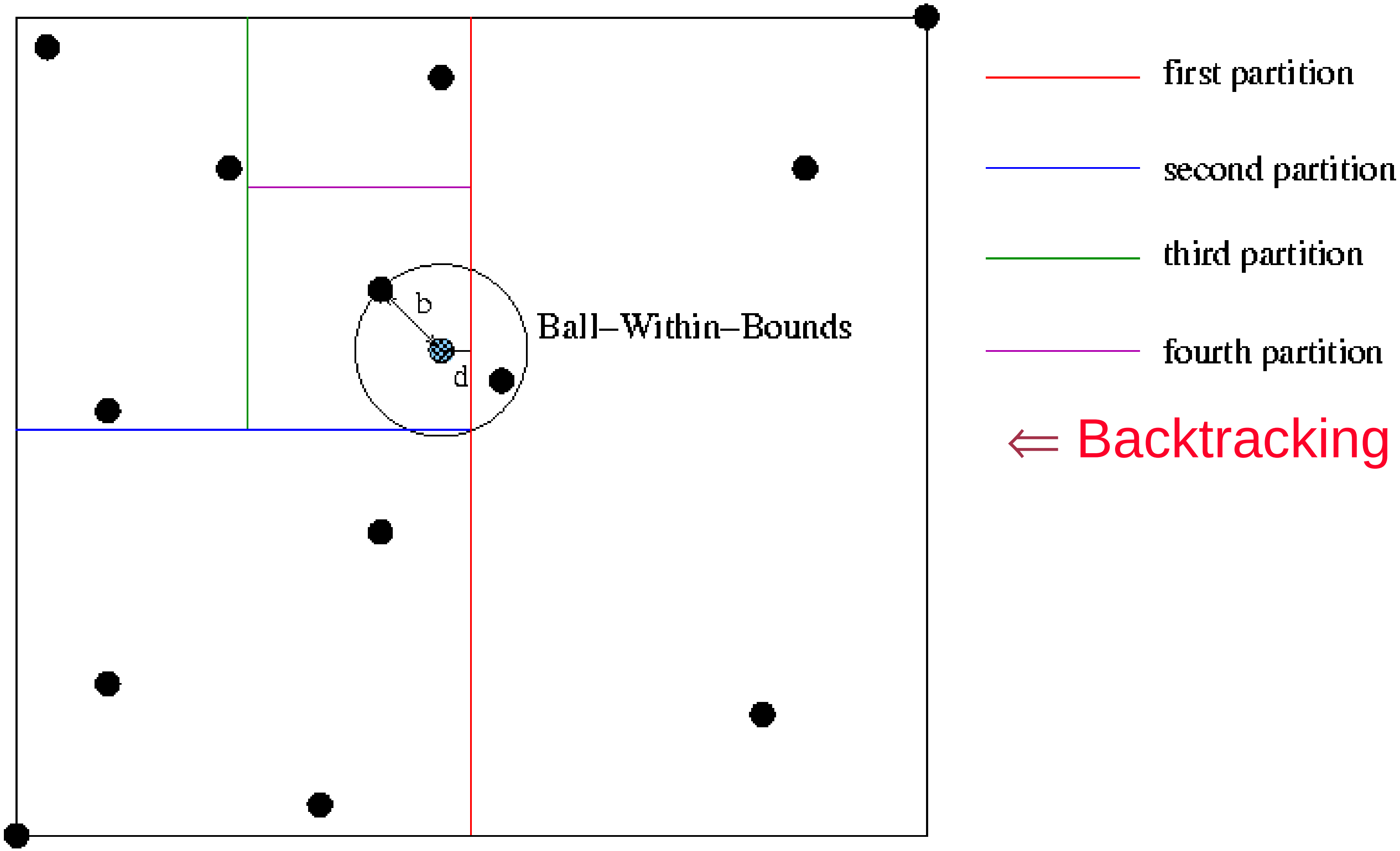
Nearest Neighbor Search



Nearest Neighbor Search

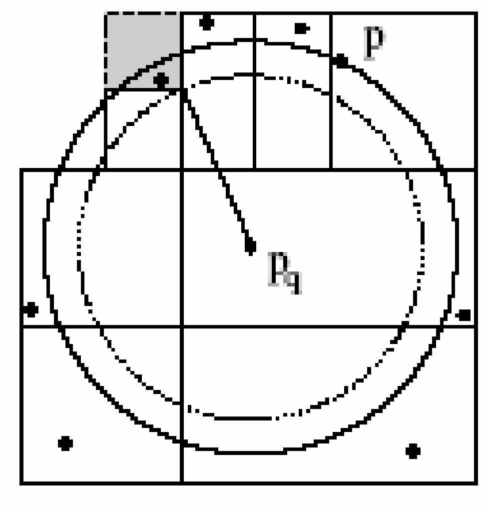


Nearest Neighbor Search



⇐ Backtracking

Approximate Nearest Neighbor Search

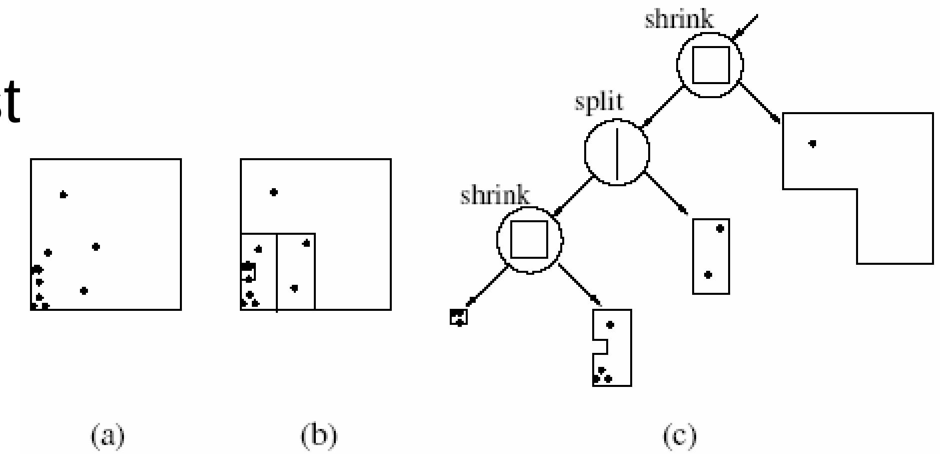


- Consider the query point p_q
- The approximate search is discontinued if the distance to the unanalyzed leaves is larger than

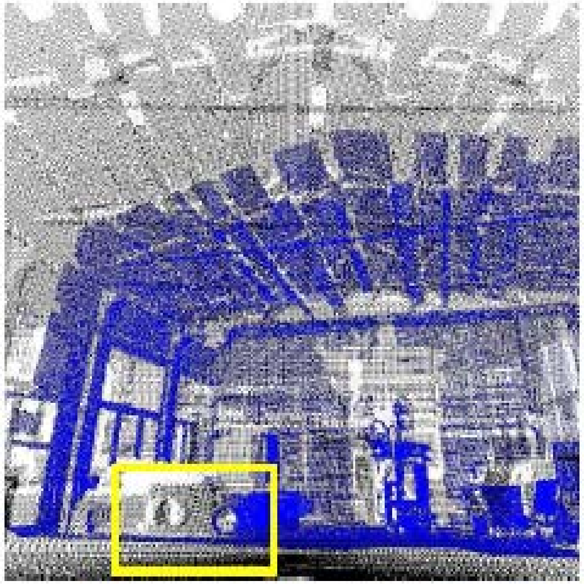
$$\|\mathbf{p}_q - \mathbf{p}\| / (1 + \varepsilon)$$

- Approximate closest point is the input for ICP

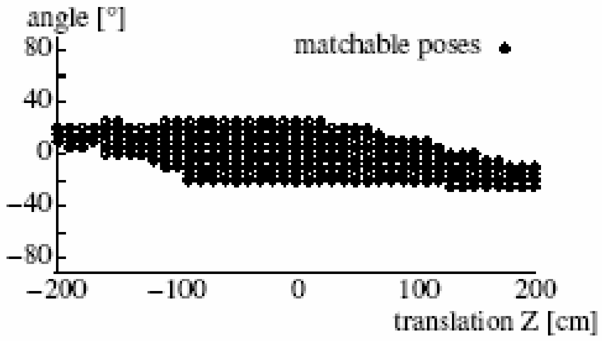
- Extreme case: Return closest point in leaf as closest point.
- Alternatively use box decomposition trees.

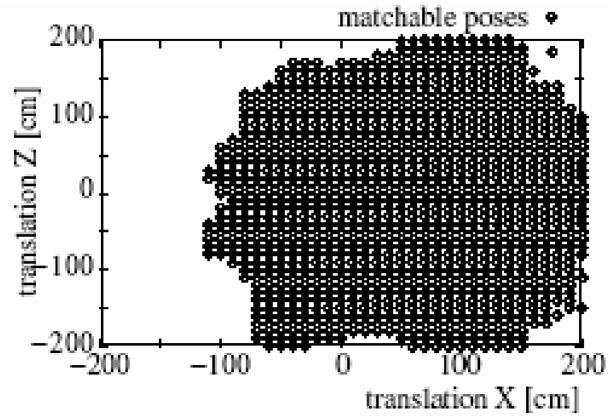


Evaluation of the ICP



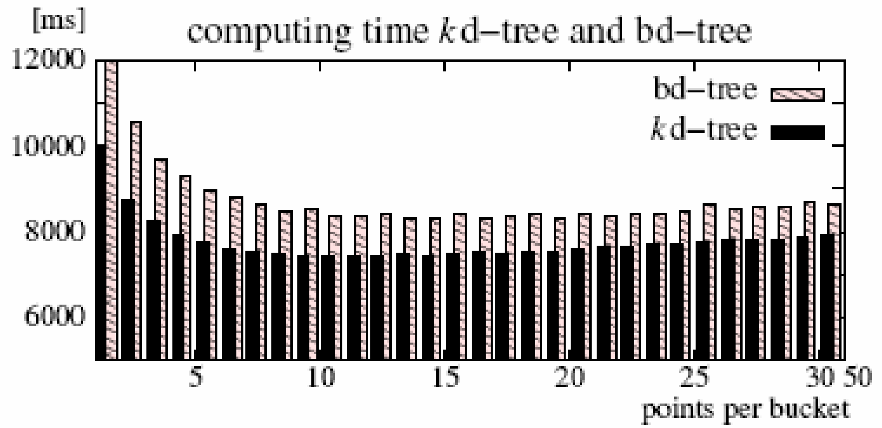
- Systematically record poses that lead to a correct match.



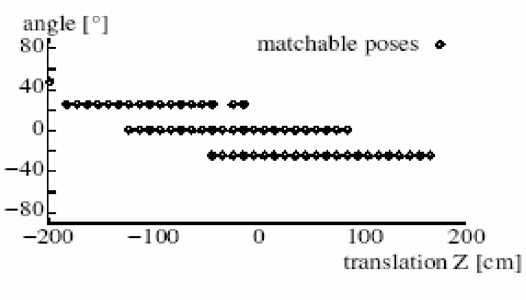


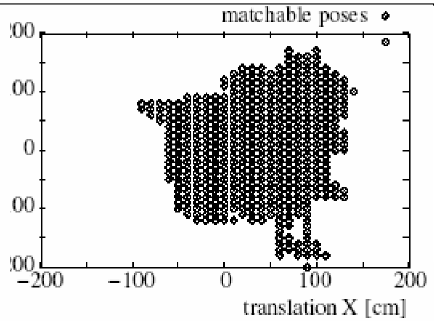
- Record scan matching time.

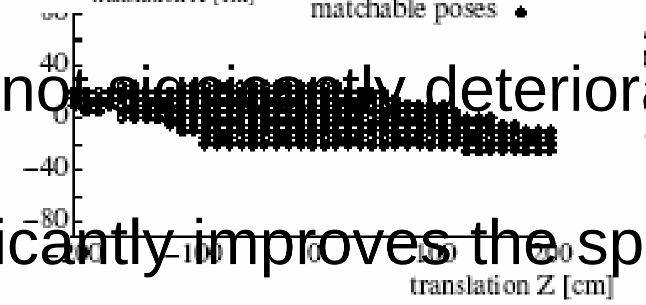
⇒ *k*d-trees outperform bd-trees

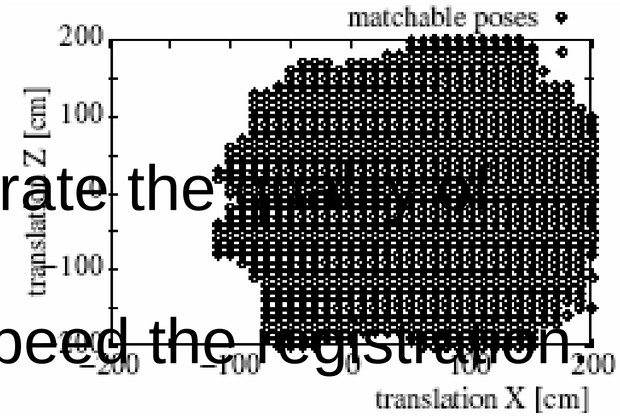


Approximation Effects to ICP

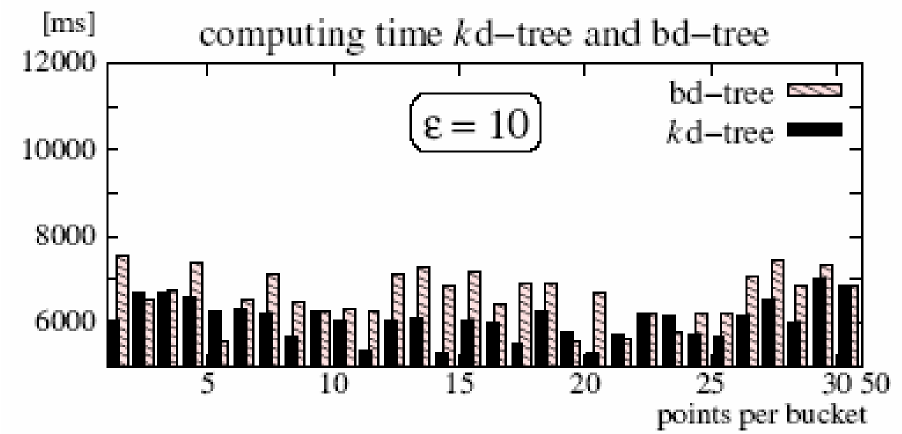








- Approximation does not significantly deteriorate the quality of scan registration.
- Approximation significantly improves the speed the registration.



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Cached kd-tree Search (1)

- In scan registration approximation is often considered critical ⇨ exact method is needed
- Recall ICP:

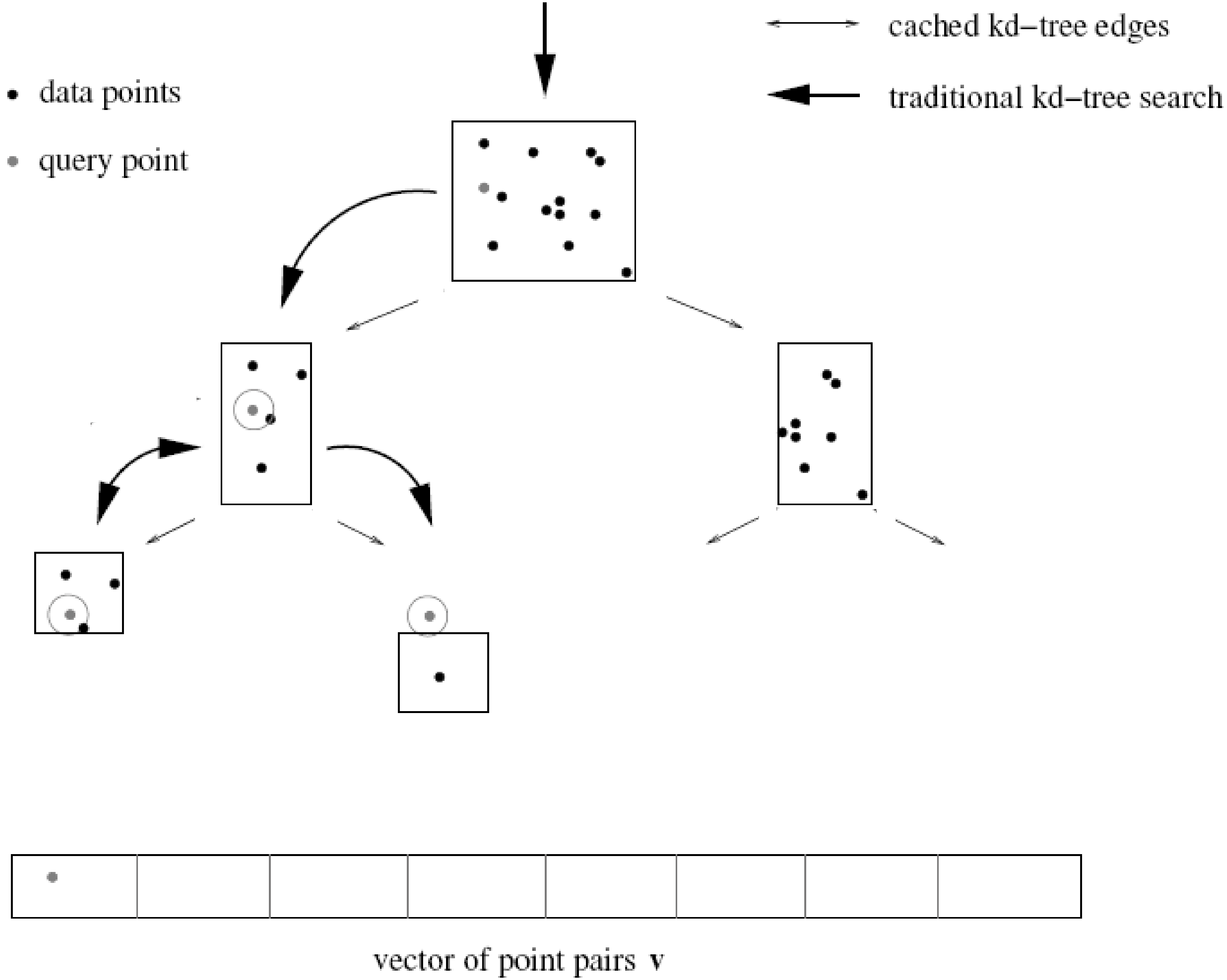
  For prior point set *M* (“model set”) and data set *D*
  1. Select point correspondences $w_{i,j}$ in {0,1}
  2. Minimize for rotation **R**, translation **t**

$$E(\mathbf{R},\mathbf{t}) = \sum_{i=1}^{N_m}\sum_{j=1}^{N_d} w_{i,j}\,||\mathbf{m}_i - (\mathbf{R}\mathbf{d}_j + \mathbf{t})||^2$$

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

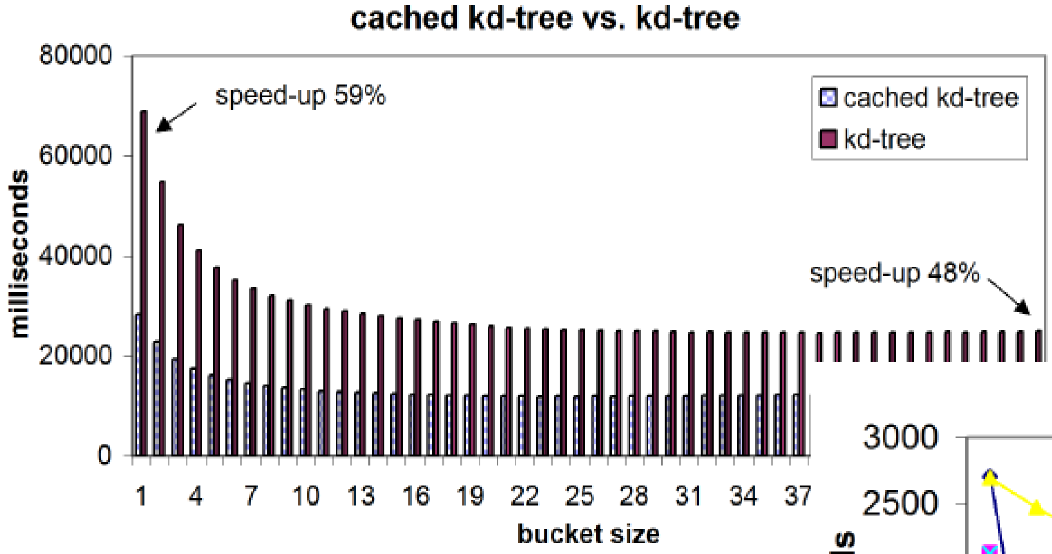
- Idea: Make use of the iterative structure of the algorithm
  – Save closest Points in a vector $\mathbf{v}$
  – In addition, we save a pointer to the leaf, where the closest point has been found
  – The kd-tree contains pointers to predecessor nodes

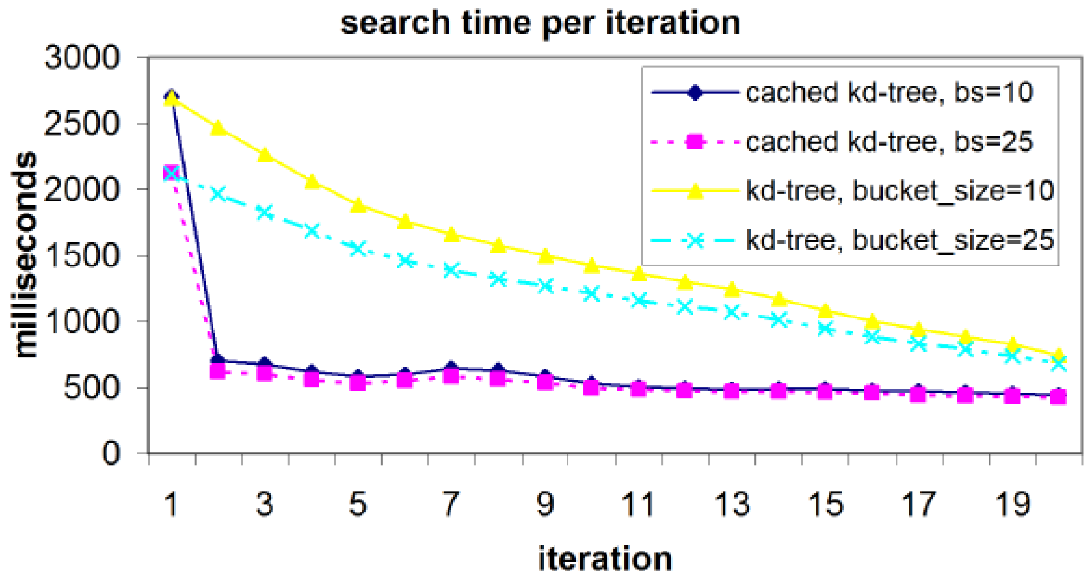
Cached kd-tree Search (2)



Cached kd-tree Search (3)

- Comparison running times





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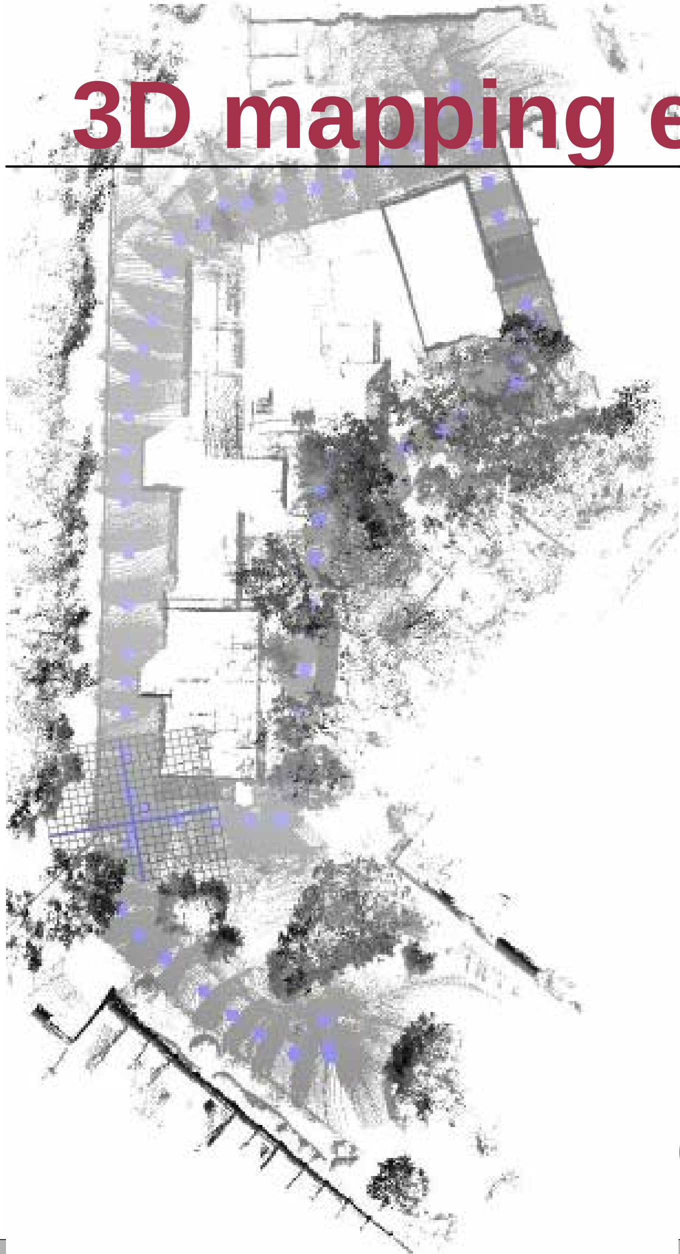
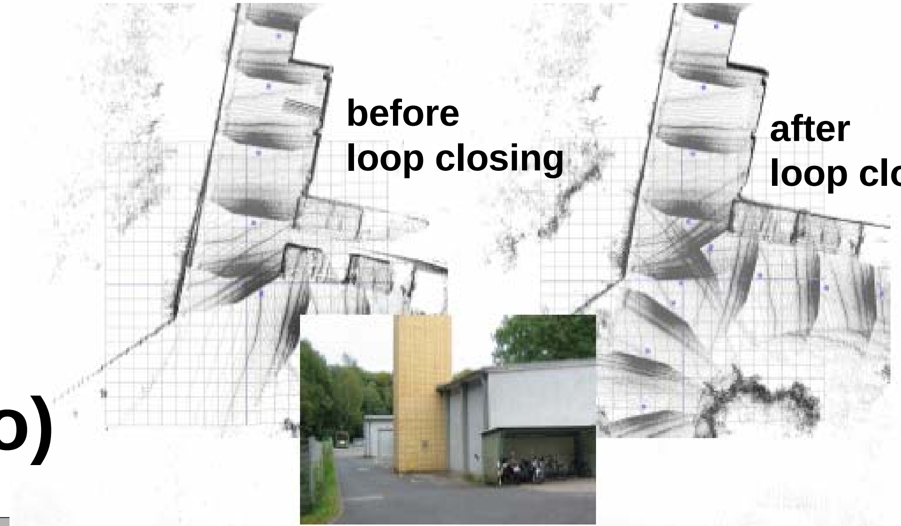
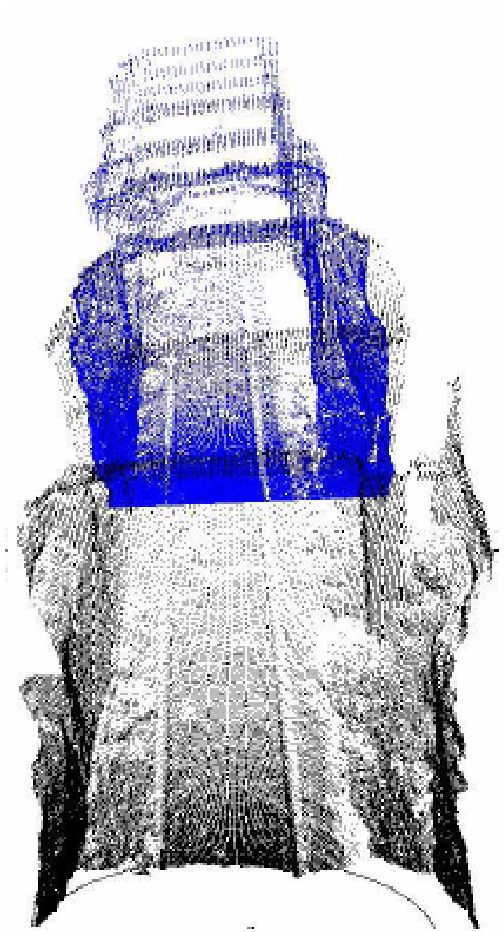
3D mapping examples





(Video)

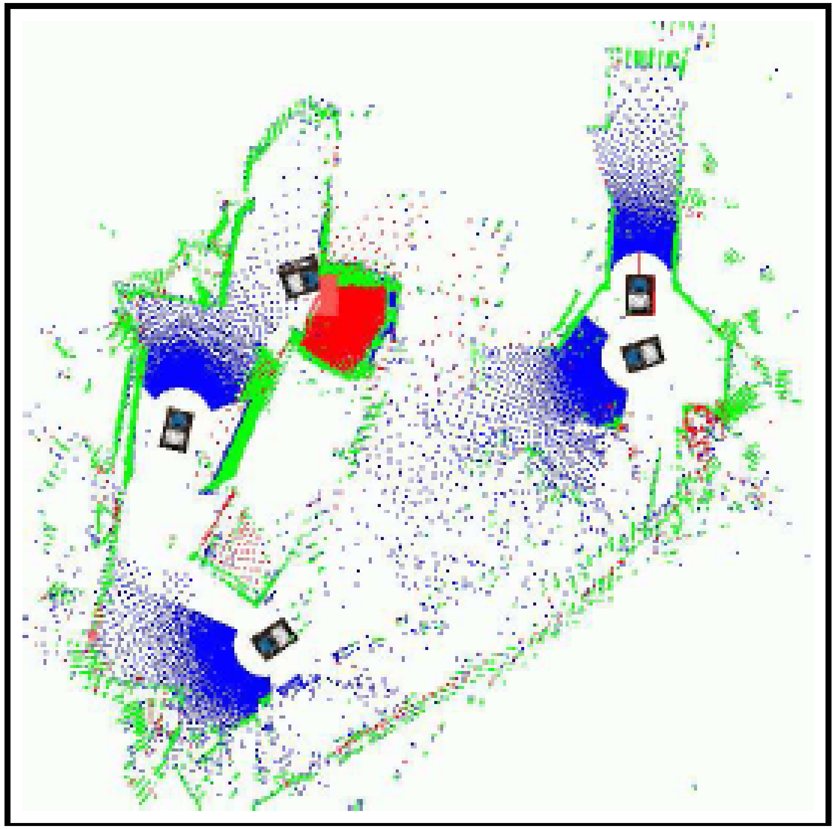
Autonomous Mine Inspection (CMU)

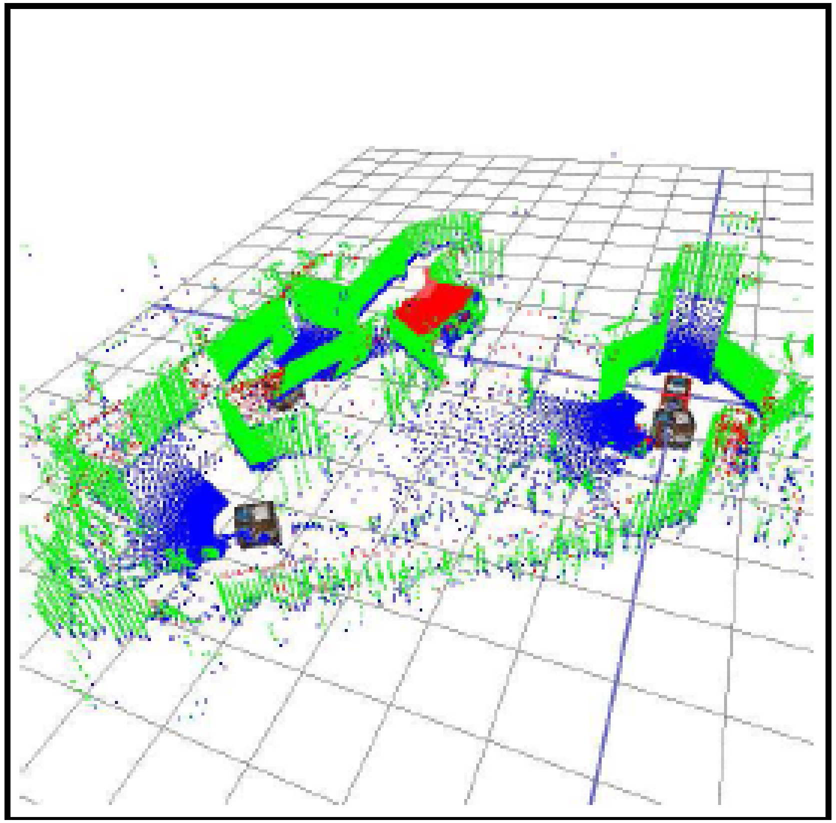


Kurt3D RoboCup Rescue (Osaka 2005)

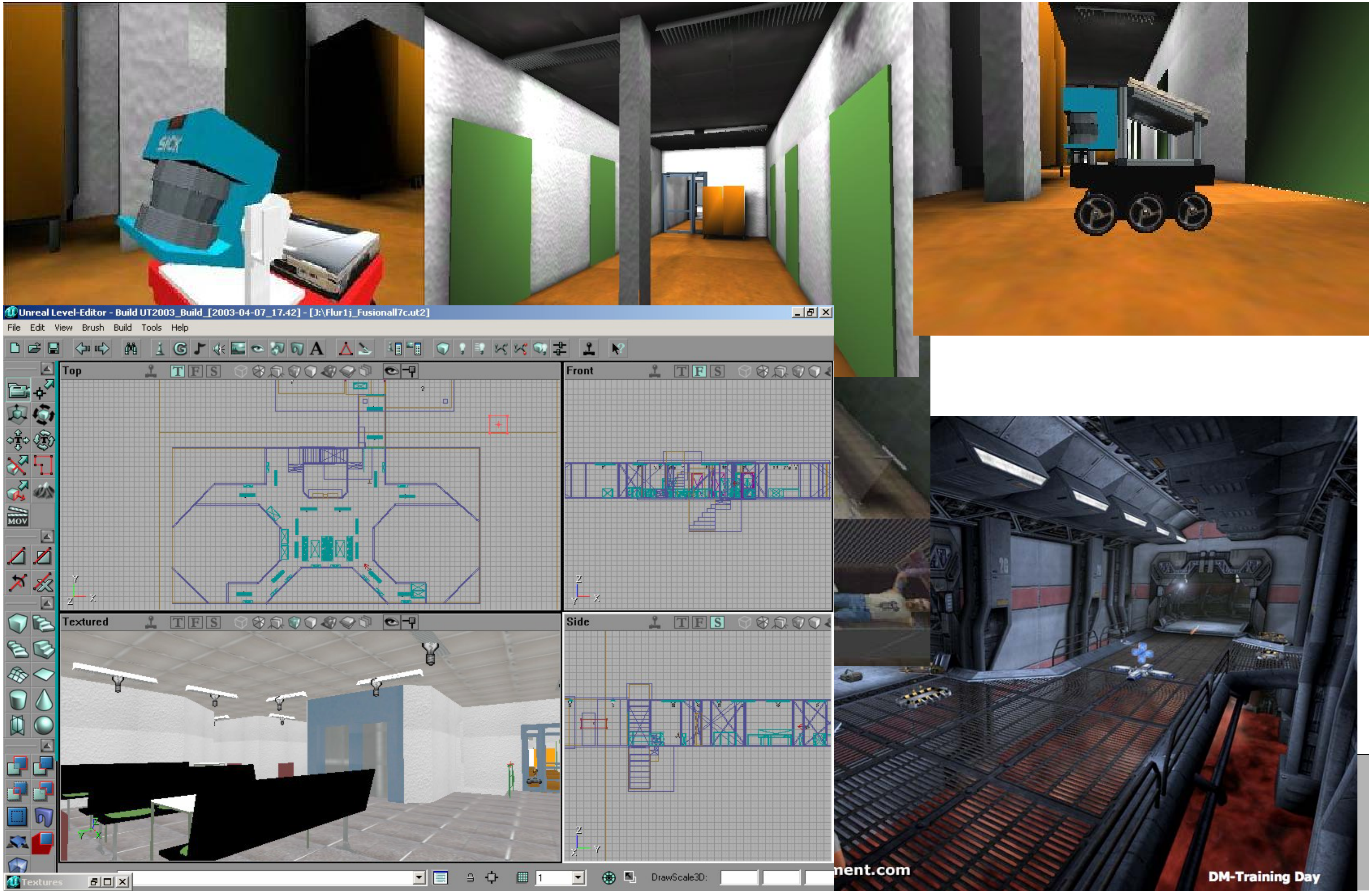
Kurt3D RoboCup Rescue (Osaka 2005)

3D maps:

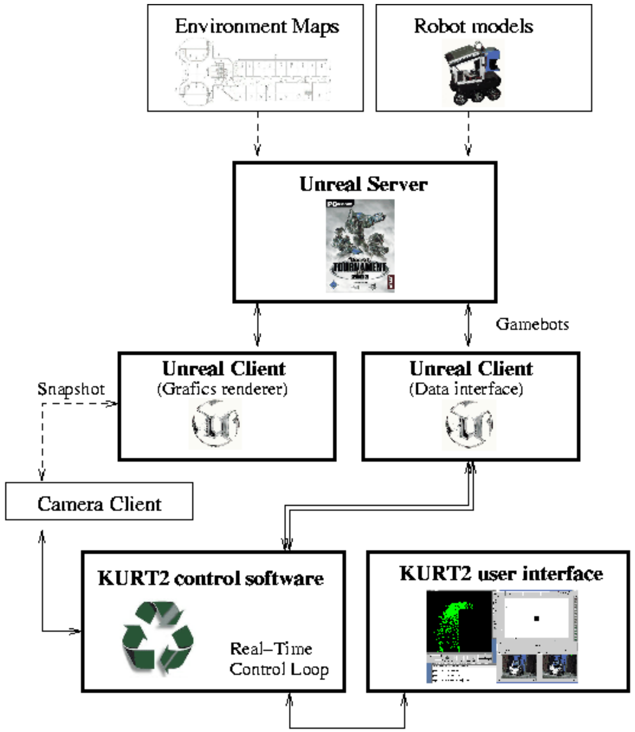




3D scans from simulation (1)

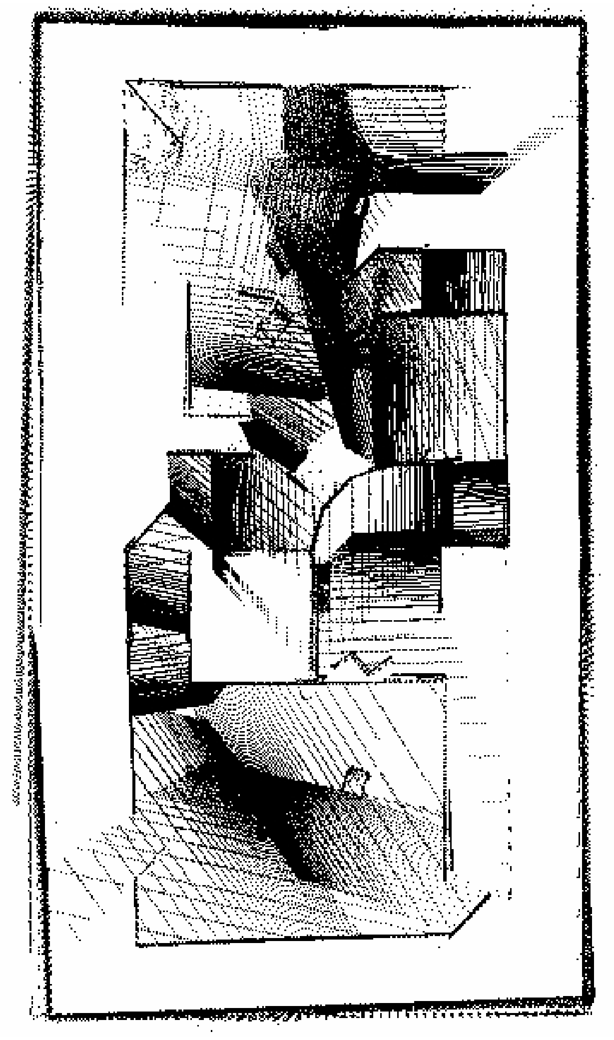


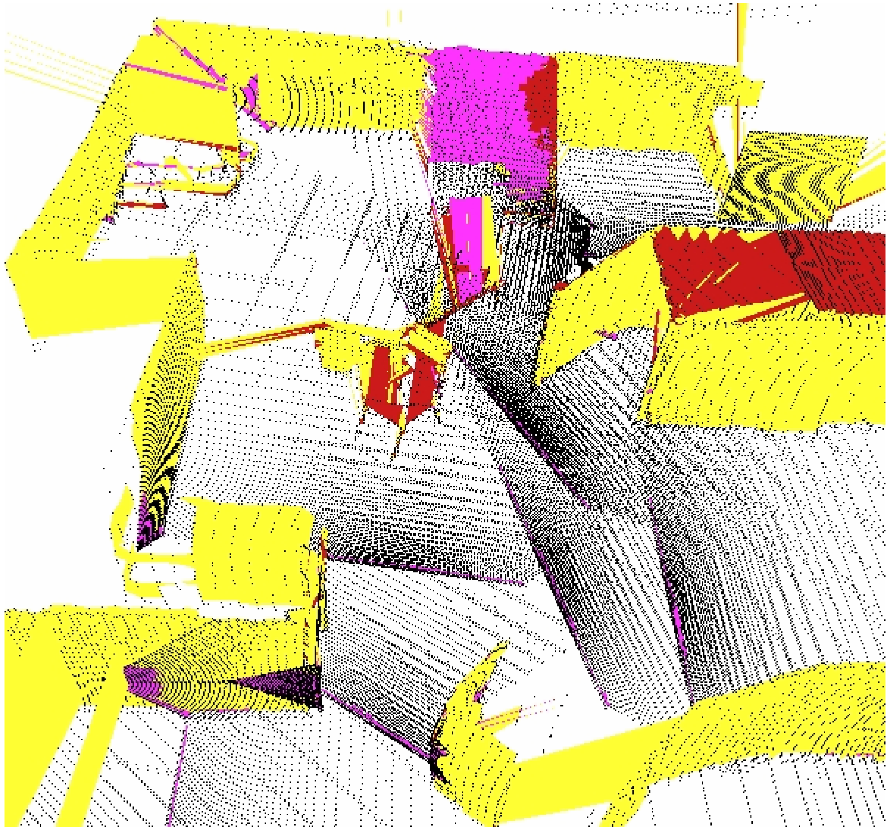
3D scans from simulation (2)



Identical interfaces !!!

3D scans from simulation (3)





- Everyone can test algorithms for robotics in 3D

Contributions

- Practical (on-line, on-board) variant of ICP for high-resolution point sets due to
  - o point reduction and
  - o efficient representation (Cached-kD-trees)
  - o starting guess based on octree representation
- Generating overall consistent 3D maps with global error minimization
- Tested on various data sets (including borrowed ones, e.g., CMU mine mapping)
- Capable of and demonstrated for full 6D SLAM
- Integrated into robot controller for 3D environment mapping
- RoboCup Rescue as evaluation for our mapping approach

  2004 second place, SSRR 2005 best paper award, 2005 6th place.

⇨ Now: SPLAM