Towards the Extraction of Hierarchical Building Descriptions from 3D Indoor Scans

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Motivation
Point clouds become more and more widely-used for tasks like

- Documenting the as-built state of buildings
- Performing fast site measurements
- Planning of retrofitting or renovation
- Generating other representations (CAD, BIM)

Images from http://www.digital210king.org/
**But**: Point clouds are mostly unstructured ("bunch of points")

- Generation of metadata and structuring cumbersome
- Usage for navigation, search, measurements, rendering, ...?
- Advantages of fast scanning partially lost again

→ Methods for automatic structuring are mandatory

*Scans of Risløkka trafikkstasjon, Oslo.*
Our approach:
Holistic hierarchical structuring of indoor point clouds.

- Hierarchy of building - storey - room - object
- Yields semantically high-level graph structure of the building
- Enables combined queries for topology and objects

Scans of Oslo Bispegård.
Related Work
Segmentation and geometric structure extraction

- **Budroni and Boehm (2010)**
  Automated 3D Reconstruction of Interiors from Point Clouds
  *International Journal of Architectural Computing*

- **Xiao and Furukawa (2012)**
  Reconstructing the World’s Museums
  *ECCV*

- **Oesau et al. (2013)**
  Indoor Scene Reconstruction Using Primitive-Driven Space Partitioning and Graph-Cut
  *Eurographics Workshop on Urban Data Modelling and Visualization*

- **Mura et al. (2013)**
  Robust Reconstruction of Interior Building Structures with Multiple Rooms under Clutter and Occlusions
  *CAD/Graphics*

- **Turner and Zakhor (2014)**
  Floor Plan Generation and Room Labeling of Indoor Environments from Laser Range Data
  *GRAPP*
Segmentation and geometric structure extraction

- Reconstruction of boundary representations from point clouds
- Some methods also include a room segmentation/labeling
- Drawback: No detection of connections between rooms

From top to bottom: Example images from Mura et al., Turner and Zakhor, Xiao and Furukawa
Scene understanding and object recognition

- **Rusu et al. (2009)**  
  Close-Range Scene Segmentation and Reconstruction of 3D Point Cloud Maps for Mobile Manipulation in Domestic Environments  
  *IROS*

- **Lai and Fox (2010)**  
  Object Recognition in 3D Point Clouds using Web Data and Domain Adaption  
  *International Journal of Robotics Research*

- **Koppula et al. (2011)**  
  Semantic Labeling of 3D Point Clouds for Indoor Scenes  
  *Advances in Neural Information Processing Systems*

- **Kim et al. (2012)**  
  Acquiring 3D Indoor Environments with Variability and Repetition  
  *ACM Transactions on Graphics*

- **Nan et al. (2012)**  
  A Search-Classify Approach for Cluttered Indoor Scene Understanding  
  *ACM Transactions on Graphics*

- **Shao et al. (2012)**  
  An Interactive Approach to Semantic Modeling of Indoor Scenes with an RGBD Camera  
  *ACM Transactions on Graphics*

- **Mattausch et al. (2014)**  
  Object Detection and Classification from Large-Scale Cluttered Indoor Scans  
  *Computer Graphics Forum*
Scene understanding and object recognition

- Recognition of objects and their relations within rooms
- Segmentation and understanding of scenes on a room-level
- Drawback: No information about overall building topology

From top to bottom: Example images from Kim et al., Koppula et al., Nan et al.
Topological structuring

- **Wessel et al. (2008)**
  The Room Connectivity Graph: Shape Retrieval in the Architectural Domain
  *WSCG*

- **Macé et al. (2010)**
  A System to Detect Rooms in Architectural Floor Plan Images
  *IAPR International Workshop on Document Analysis Systems*

- **Ahmed et al. (2012)**
  Automatic Room Detection and Room Labeling from Architectural Floor Plans
  *Document Analysis Systems*

- **Langenhan et al. (2013)**
  Graph-Based Retrieval of Building Information Models for Supporting the Early Design Stages
  *Advanced Engineering Informatics*

- **Ahmed et al. (2014)**
  Automatic Analysis and Sketch-Based Retrieval of Architectural Floor Plans
  *Pattern Recognition Letters*

- **Ochmann et al. (2014)**
  Automatic Generation of Structural Building Descriptions from 3D Point Cloud Scans
  *GRAPP*
Topological structuring

- Extraction of structure, connectivity, accessibility of rooms
- Using different representations (2D plans, 3D CAD, BIM)
- Drawback: Rely on the availability of such representations
- (Except for Ochmann et al.; will be revisited later)

From left to right: Example images from Langenhan et al., Macé et al., Wessel et al.
Rooms and Storeys
Room segmentation:
The task is to find a decomposition into single rooms.

Scans of a building in Denmark.
• **Starting point:** Multiple, globally registered scans
• Point normals are computed by means of local PCA
• Merge scans which belong to the same room
• Done interactively in the scope of this work

Scans of a building in Denmark.
• Even after merging, large incorrectly labeled regions exist
• Need to resolve ambiguities where multiple scans overlap

Scans of a building in Denmark.
- **Idea:** Use the labeling we have up to now as a starting point
- **Assume:** Most points *visible* from $x$ belong to same room as $x$

*Scans of a building in Denmark.*
• Perform stochastic ray casting to sample visible points
• Determine labels of points that were hit

Scans of a building in Denmark.
• Gather and average all “observed” labels
• Assign average (soft) label vector to $\mathbf{x}$

Scans of a building in Denmark.
• Iterate the process a few times ("allow ray bounces")
• Yields a "diffusion" of labels governed by visibility
Importance of allowing some recursion:

Scans from Kronborg Castle, Denmark. Initial labeling.
Importance of allowing some recursion:

*Scans from Kronborg Castle, Denmark. After 1 iteration.*
Importance of allowing some recursion:

Scans from Kronborg Castle, Denmark. After 2 iterations.
Importance of allowing some recursion:

*Scans from Kronborg Castle, Denmark. After 5 iterations.*
Note on ray-cloud intersection tests:

- Detect planar structures including occupancy bitmaps
- Search for nearest intersections during ray traversal
- Using OpenCL for parallel computation on GPU

*Scans of a building in Denmark.*
Further steps after room segmentation:

- Approximate room areas are computed (projection of points belonging to horizontal planes into bitmap with known pixel size in x-y-plane, count filled pixels)

\[ \sim 44.5 \text{ m}^2 \]
Further steps after room segmentation:

- Binning of room floor planes (largest plane with normal pointing upwards) to determine storeys
Connectivity
**Room neighborhood and connectivity:**
Determine room adjacency and openings between rooms.

*Scans of a building of the Technical University of Denmark.*
Determination of room neighborhood:

- Determine walls shared by adjacent rooms (find pairs of planes fulfilling distance/angle/overlap constraints)
- For each determined neighbor relation, insert edge between respective room nodes, including set of shared planes
Determination of connections:

Scans of Oslo Bispegård.

Door to detect

Labeling changed from "red" to "green" here
Determination of connections:

Scans of Oslo Bispegård.
Determination of connections:

- Cast rays from "red" scanner position
- Compute intersections with planes associated with room neighbor edges

Scans of Oslo Bispegården.
Determination of connections:

Compute intersections with planes associated with room neighbor edges

Intersection points yield estimate for door position and geometry

Scans of Oslo Bispegård.
Example for extracted room connectivity graph
Idea of room segmentation partially based on our paper:

**Ochmann, Vock, Wessel, Klein**

Automatic Generation of Structural Building Descriptions from 3D Point Cloud Scans (*GRAPP* 2014)

- Room segmentation using a probabilistic clustering approach
- Detection of openings between rooms

In contrast to the above-mentioned paper, we...

- are able to cope with highly non-convex rooms
- extract room neighborhood information
- have a more robust door detection
- incorporate vertical connections
Objects
Extension of the building graph by information about objects contained within each room

*Scans of Oslo Bispegård. Extracted object segments are highlighted.*
• Object segmentation performed on a per-room level
• Remove outlier points (i.e. high distance to neighbors)
• Remove points which belong to planar structures
• Perform connected component analysis on remaining points
Geometric shape descriptor for each segment

- Global descriptor, spatial division in sectors, shells, slices
- Bottom of descriptor aligned with room’s floor elevation
- Compare histograms using (symmetric) $\chi^2$ distance
- Rotation invariance along “up” direction by comparing all possible shifts of sectors when comparing two descriptors
- Add descriptors for combinations of up to three segments to mitigate problem of oversegmentation
Example for object query using a segment from the cloud itself

Scans of Oslo Bispegård.
Matching
Combined queries for room constellations and objects may be performed by searching for attributed subgraphs.
Graph matching is performed by finding *subgraph monomorphisms*

- Attributes: Node types, room area, object descriptors, horizontal/vertical room connections
- When matching object nodes, distance between descriptors is taken into account in match score
- Example-based queries for objects based on mesh models or point clouds

*Scans of Risløkka trafikkstasjon, Oslo.*
Example for a coarse query for storey nodes

*Scans of Risløkka trafikkstasjon, Oslo.*
Derive functionality of rooms (e.g. many tables $\rightarrow$ seminar room)

Scans of Risløkka trafikkstasjon, Oslo.
Combine topological, semantic and geometric queries

Scans of Risløkka trafikkstasjon, Oslo.
Conclusion
In summary:

- We demonstrated a holistic approach for the extraction of hierarchical building descriptors purely from point clouds.
- Modular processing chain allows exchange or improvement of each component.
- Segmentation into storeys and rooms enables easy navigation and topological queries.
- Extension by room attributes and object descriptors allow targeted queries beyond room constellations.
Future work:

- Add more fine-grained information (e.g. relations between objects, more attributes)
- Different kinds of queries (using grammars, shortest paths, ...)
- Comparison of buildings or parts of buildings (e.g. via graph edit distances)
Thank you