

Automatic Generation of Structural Building Descriptions from 3D Point Cloud Scans

Sebastian Ochmann¹, Richard Vock¹, Raoul Wessel¹, Martin Tamke² and Reinhard Klein¹

¹*Institute of Computer Science II, University of Bonn, Bonn, Germany*

²*Centre for Information Technology and Architecture (CITA), The Royal Danish Academy of Fine Arts, School of Architecture, Copenhagen, Denmark*

Keywords: Scene Understanding, Building Structure, Point Cloud, Laser Scanning, Segmentation.

Abstract: We present a new method for automatic semantic structuring of 3D point clouds representing buildings. In contrast to existing approaches which either target the outside appearance like the facade structure or rather low-level geometric structures, we focus on the building's interior using indoor scans to derive high-level architectural entities like rooms and doors. Starting with a registered 3D point cloud, we probabilistically model the affiliation of each measured point to a certain room in the building. We solve the resulting clustering problem using an iterative algorithm that relies on the estimated visibilities between any two locations within the point cloud. With the segmentation into rooms at hand, we subsequently determine the locations and extents of doors between adjacent rooms. In our experiments, we demonstrate the feasibility of our method by applying it to synthetic as well as to real-world data.

1 INTRODUCTION

Digital 3D representations of buildings highly differ regarding the amount of inherent structuring. On the one hand, new building drafts are mainly created using state-of-the-art Building Information Modeling (BIM) approaches that naturally ensure a high amount of structuring into semantic entities ranging e.g. from storeys and rooms over walls down to doors and windows. On the other hand, 3D point cloud scans, which today are increasingly used as a documentation tool for already existing, older buildings, are almost completely unstructured. The semantic gap between such low- and high-level representations hinders the efficient usage of 3D point cloud scans for various purposes including retrofitting, renovation, and semantic analysis of the legacy building stock, for which no structured digital representations exist. As a solution, architects and construction companies usually use the measured point cloud data to manually generate a 3D BIM overlay that provides enough structuring to allow easy navigation and computation of key properties like room or window area. However, this task is both cumbersome and time-consuming.

While existing approaches for building structuring either require 3D CAD models (Wessel et al., 2008; Langenhan et al., 2012), consider primarily outdoor

(airborne) scans (Verma et al., 2006; Schnabel et al., 2008; Bokeloh et al., 2009), or target the recognition of objects like furniture inside single rooms (Kim et al., 2012; Nan et al., 2012), our method focuses on the extraction of the overall room structure from indoor 3D point cloud scans. We aim at first decomposing the point cloud such that each point is assigned to a room. To this end, we propose a probabilistic clustering algorithm that exploits knowledge about the belonging of each measured point to a particular scan. The resulting segmentation constitutes the fundamental building block for computing important key properties like e.g. room area. In a second step we detect doors connecting the rooms and construct a graph that encodes the building topology.

Our method may be summarized as follows (see also Figure 1): We start with multiple indoor 3D point clouds scans which have been registered beforehand (this step is not in the scope of this paper). Each point is initially labeled with an index of the scan from which it originates. In a preprocessing step, normals are estimated for each point (if necessary) and planar structures are detected using the algorithm by (Schnabel et al., 2007). This yields a set of planes together with subsets of points corresponding to each plane. Next, point sets belonging to scanning positions that are located in the same room are merged; this affects

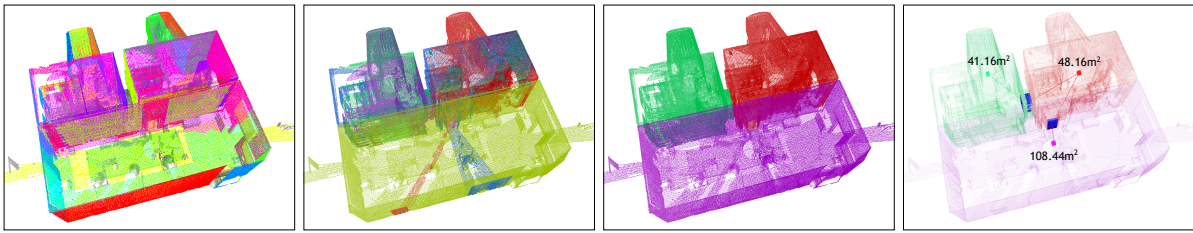


Figure 1: Overview of our method. From left to right: Detected planar structures; colour-coded indices of the individual scans; final point assignments after the re-labeling process; extracted room topology graph.

those rooms in which scans from multiple positions were performed. This step may be either performed automatically or semi-automatically using a graphical user interface for correcting automatically generated results. Following the merging step, an iterative re-labeling process is performed to update assignments of points to rooms. This process uses a probabilistic model to estimate updated soft assignments of points to room labels. After convergence, a new (hard) assignment of points to rooms is obtained.

Finally, the original and the new labeling of the points are used to determine the locations and extents of doors between pairs of adjacent rooms. Together with the set of room points, this constitutes a room connectivity graph in which rooms are represented by attributed nodes and doors are represented by edges. Such representations are an important tool for semantic building analysis or graph-based building retrieval (Wessel et al., 2008; Langenhan et al., 2012).

The contributions of this paper are:

1. Automatic decomposition of a 3D indoor building scan into rooms.
2. A method for detecting connections between adjacent rooms using the computed decomposition.
3. Construction of a graph encoding the building's topology purely from point clouds.

2 RELATED WORK

In this Section we briefly review the related work on the extraction of structural building information from digital representations.

2.1 Point-cloud-based Approaches

In (Verma et al., 2006) a parametric shape grammar is used to detect common roof shapes in LIDAR data. They initially extract connected components of planar point sets and filter out small components in order to get separated subsets of points for ground and roof structures. Subsequently arbitrary polygons are fitted

to the roof and by analyzing their topological relations, simple, parameterized roof shapes are matched to the scan data. This approach is rather specific to roof shape detection, where a concise, parametric model for detected objects can be derived. By representing point clouds as a topology graph of inter-related basic shape primitives (Schnabel et al., 2008) reduce the problem of finding shapes in point clouds to a subgraph matching problem. The scene as well as the query object are decomposed into primitive shapes using a RANSAC (random sample consensus) approach. A topology graph for each cloud is constructed capturing the spatial relationships between these primitive shapes. A lot of research has recently been conducted in exploiting symmetries in order to understand scan data. For example (Bokeloh et al., 2009) detect partial symmetries in point cloud data by matching line features detected using slippage analysis of point neighbourhoods in a moving least squares scheme. Matching these line features and extracting symmetric components yields a decomposition of the scanned scene into cliques of symmetric parts. These parts however do not necessarily carry a semantic meaning in architectural terms and are therefore not suited for semantic analysis of building structures.

While the above methods are used to structure scans showing the outside of a building, the interior of buildings has recently gained attention, especially in the field of robotics, where segmentation of furniture is an important topic for indoor navigation, see e.g. (Rusu et al., 2008; Koppula et al., 2011). An iterative search-and-classify method is used by (Nan et al., 2012) for segmentation of indoor scenes. They start with an over-segmented scene and iteratively grow regions while maximizing classification likelihood. A similar, supervised learning approach is used by (Kim et al., 2012). Their method is divided into a learning phase, in which multiple scans of single objects are processed in order to obtain a decomposition into simple parts as well as to derive their spatial relations, and a recognition phase. Both of these methods focus on the recognition of objects like furniture that can be well represented by certain templates and do not take the overall room structure of a building into account.

2.2 Approaches based on Alternative Representations

(Wessel et al., 2008) extract topological information from low-level 3D CAD representations of buildings. They find floor planes in the input polygon soup and extract 2D plans by cutting each storey at different heights. These cuts are then analyzed in order to extract rooms and inconsistencies between different cut heights yield candidates for doors and windows. In (Langenhan et al., 2013), high-level BIM models are used for the extraction of a building's topology. They derive information about the topological relationship between rooms from IFC (Industry Foundation Classes) files by analysis of certain entity constellations which can be used to perform sketch-based queries in a database. (Ahmed et al., 2012) use 2D floor plans to extract the structure and semantics of buildings. The input drawing is first segmented into graphical parts of differing line thickness used to extract the geometry of rooms by means of contour detection and symbol matching, and a textual part used for semantic enrichment by means of OCR (optical character recognition) and subsequent matching with predefined room labels. A hybrid approach is presented in (Xiao and Furukawa, 2012). The authors use 3D point cloud data together with ground-level photographs to reconstruct a CSG representation based on fitted rectangle primitives. Note that this work rather focuses on indoor scene reconstruction than on the actual extraction of a semantic structuring.

3 PREPROCESSING

The input data for our method consists of multiple 3D point clouds which have been registered beforehand in a common world coordinate system. The registration step is usually done automatically or semi-automatically by the scanner software and is not in the scope of this paper. Each individual scan also contains the scanner position.

If normals are not part of the input data, they are approximated by means of local PCA (principal component analysis) of point patches around the individual data points. To determine the correct orientation of the normal, it is checked whether the determined normal vector points into the hemisphere in which the scanner position associated with the point is located.

Subsequently, planar structures are detected in the whole point cloud using a RANSAC algorithm by (Schnabel et al., 2007). This yields a set of planes defined by their normal and distance to the origin. Additionally, the association between each plane $p \in \mathcal{P}$ and

the point set P_p that constitutes this plane is stored.

The known assignments of points to the individual scans will be used in the next section as an initial guess which points belong to a room. As one particular room may have been scanned from more than one scanner location, scans belonging to the same room are merged. This step is performed in a semi-automatic manner. A conservative measure whether two scans belong to the same room is used to give the user suggestions which scans should be merged. This measure takes into account the ratio of overlapping points between two scans to the total number of involved points. If the ratio is above a certain threshold, the rooms are suggested to be merged. The user may choose to accept these suggestions or make manual changes as desired. Note that the original scanner positions are stored for later usage, together with the information which scans were merged.

4 PROBABILISTIC POINT-TO-ROOM LABELING

After the merging step described in Section 3, we are left with m different room labels and their associated points. In the following, we describe the task of point-to-room assignment as a probabilistic clustering problem (Duda et al., 2001). Let $\omega_j, j = 1, \dots, m$ denote the random variable that indicates a particular room, and furthermore, let x denote a random variable corresponding to a point in \mathbb{R}^3 . Then the class-conditional densities $p(x|\omega_j)$ describe the probability for observing a point x given the existence of the j th room. By that, we can describe the problem of segmenting a point cloud into single rooms by computing the conditional probability $p(\omega_j|x)$ that an observed point x belongs to the j th room. Given a particular observation x_k from the point cloud scan, we can determine its probabilistic room assignment by computing

$$p(\omega_j|x_k) = \frac{p(x_k|\omega_j)p(\omega_j)}{\sum_{j'=1}^m p(x_k|\omega_{j'})p(\omega_{j'})}. \quad (1)$$

From the above equation it becomes clear that determining the clustering actually boils down to modeling and computing the class-conditional probabilities. Intuitively speaking, for a particular room $p(x_k|\omega_j)$ should provide a high value if the observed measurement x_k lies inside it. Suppose we already knew a set of points \bar{X}_j that belongs to the room. A good choice to decide whether an observation lies inside would be to consider the visibility $v_j(x_k) \in [0, 1]$ of this particular point from all the other points in \bar{X}_j that we know belong to the room (we will describe how to estimate the visibility in detail in Section 5).

In order to steer the impact of varying visibilities we formulate the class-conditional probability in terms of a normal distribution over the visibilities:

$$p(x_k|\omega_j, \sigma) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(1-v_j(x_k))^2}{2\sigma^2}\right). \quad (2)$$

Apparently, computing the visibility $v_j(x_k)$ requires knowledge about the exact dimensions of the room, rendering the underlying clustering a chicken-egg problem. We alleviate by starting with an educated guess about the point-to-room assignments, which is given by the information which points originate from the individual (merged) scans. This prior knowledge is used to compute $v_j(x_k)$ in the first iteration. We then iterate between the cluster assignment and visibility computation until our algorithm converges. In Algorithm 1, we show an overview of the iterative assignment process.

Data: A set of observations $x_k \in \mathbb{R}^3, k = 1, \dots, n$

Data: A set of initial room assignments:

$$\forall k \exists r_{init}(x_k) \in \{1, \dots, m\}$$

Data: A set of planes $p_i \in \mathcal{P}, i = 1, \dots, |\mathcal{P}|$

Result: A new point-to-room assignment:

$$\forall k \exists r_{final}(x_k) \in \{1, \dots, m\}$$

Initialize prior room probabilities according to number of measured points:

$$p(\omega_j) := \frac{|\{r_{init}(x_k)=j, k=1, \dots, n\}|}{\sum_{j'=1}^m |\{r_{init}(x_k)=j', k=1, \dots, n\}|};$$

Initialize $r_{curr}(x_k) := r_{init}(x_k)$;

while not converged do

 Compute the set of points belonging to the

j th room: $\bar{X}_j := \{x | r_{curr}(x) = j\}$;

 Compute class-conditional probabilities:

$$p(x_k|\omega_j, \sigma) := \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(1-v_j(x_k))^2}{2\sigma^2}\right);$$

 Compute probabilistic cluster assignments:

$$p(\omega_j|x_k) = \frac{p(x_k|\omega_j)p(\omega_j)}{\sum_{j'=1}^m p(x_k|\omega_{j'})p(\omega_{j'})};$$

 Compute hard cluster assignments:

$$r_{curr}(x_k) = \arg \max_{j=1, \dots, m} p(\omega_j|x_k);$$

 Renormalize room priors:

$$p(\omega_j) := \frac{1}{n} \sum_{k=1}^n p(\omega_j|x_k)$$

end

$r_{final}(x_k) := r_{curr}(x_k)$;

Algorithm 1: Iterative room-to-point assignment.

In our tests we use a fixed σ throughout the iterations and for all rooms (see Section 9). Note however that it might improve results if for each room individual σ_j would be used. Estimation of σ_j and computation of the soft assignments could be carried out using an expectation-maximization (EM) algorithm (Dempster et al., 1977).

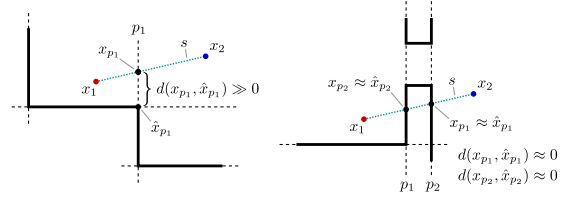


Figure 2: Different cases of visibility estimation. Left: Visibility between two points x_1, x_2 located within a room. The line-of-sight is unobstructed since line segment s does not intersect any building structure. Right: If a wall lies between x_1, x_2 , s intersects multiple planes and visibility is estimated to be low.

5 VISIBILITY ESTIMATION

We construct the visibility function $v_j(x_k)$ to estimate how unobstructed the line-of-sights between a point x_k to all (or a sampled subset of) points \bar{X}_j of the j th room are on average.

The intuition behind this functional is depicted in Figure 2. If we wish to estimate the visibility between the points x_1 and x_2 , we take into account the set of planes p_i that are intersected by the line segment s between the two points. For intersection testing, we consider the complete infinitely large plane. Because a plane p_i is only constituted by a subset of the measured points, the line segment s passing through that plane shall only be considered to be highly obstructed if measured points exist in the vicinity of the intersection point. Let x_{p_i} be the intersection point of s with plane p_i and let \hat{x}_{p_i} be the point belonging to the plane p_i which is closest to x_{p_i} :

$$\hat{x}_{p_i} := \operatorname{argmin}_{x \in P_p} \|x - x_{p_i}\|_2. \quad (3)$$

The left half of Figure 2 shows the situation that s is located completely inside a single room. Note that, in this case, $d(x_{p_1}, \hat{x}_{p_1})$ is large and thus the visibility regarding plane p_1 is high. In the right half, the situation of s crossing through a wall is shown. In this case, the distances $d(x_{p_1}, \hat{x}_{p_1})$ and $d(x_{p_2}, \hat{x}_{p_2})$ to the nearest points in the planes are (almost) zero and thus the estimate of the visibility between the points is low.

Let p be a plane and x_p the intersection of s with p . Furthermore, for the set of planes \mathcal{P} and the set of all measured points X , let

$$v_p(x_1, x_2, p) : X \times X \times \mathcal{P} \rightarrow [0, 1] \quad (4)$$

be a function estimating the visibility between x_1 and x_2 with respect to a plane p following the above intuition which yields a high value iff the line-of-sight is unobstructed (see Section 9 for implementation details).

The visibility term over all planes $\bar{\mathcal{P}}$ which s intersects is defined as

$$v_{\bar{\mathcal{P}}}(x_1, x_2) := \frac{1}{1 + \sum_{p \in \bar{\mathcal{P}}} (1 - v_p(x_1, x_2, p))}. \quad (5)$$

Intuitively speaking, the more planes with low visibility values are encountered along the line segment, the more the total visibility value decreases. Finally, we use Equation (5) to define the average visibility from a point x_k to a point set \bar{X}_j containing points labeled to belong to the j th room:

$$v_j(x_k) := \frac{\sum_{x \in \bar{X}_j} v_{\bar{\mathcal{P}}}(x_k, x)}{|\bar{X}_j|}. \quad (6)$$

6 DOOR DETECTION

The presence of a door causes the points from one single scan to belong to at least two different semantic rooms. As a consequence, when considering a point that changed the room assignment during our probabilistic relabeling, the associated ray must have been shot through a connecting door. We exploit this observation for our door localization method. Note that this requires the doors to stand open during the scanning process. This assumption is justified as overlaps between scans are usually required for registration.

In preparation for door detection, we create a mapping of planes to rooms by iterating through the set of planes and counting the number of points on that plane that are labeled to be part of the individual rooms. If the number of points belonging to room r exceeds a threshold, the plane as well as the subset of points is assigned to r . This process may also assign one plane to multiple rooms but its constituting point set is split among the rooms sharing this plane.

The next step is the generation of candidate point sets that may constitute the coarse shape of one side of a door opening. Consider a room r consisting of scanner positions s_0, \dots, s_n . We are interested in those rays going from s_i through the position of the associated point p_i where the labeling of p_i has changed during the segmentation step. For each such ray, we check for intersections with each plane belonging to room r (Figure 3, left). This yields co-planar point sets which are stored together with the information which room s_i belongs to, which room the point p_i belongs to and which plane was intersected (Figure 3, middle).

After the candidates have been constructed, we split the point sets of each candidate into connected components. This is necessary if a room pair is connected through multiple doors lying in the same plane.

In a final step, pairs of candidates fulfilling certain constraints are extracted. The first constraint forces

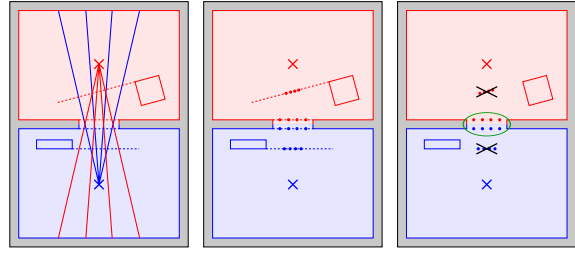


Figure 3: For door detection, the rays whose target point's labeling has changed during segmentation are intersected with the planes belonging to the room in which the scanner is located (left); the intersection point sets on each plane are potential door candidates (middle); pairs of candidates that fulfill certain constraints are extracted (right).

the normals of the two involved planes to point away from each other. The second constraint forces the distance between the planes to be within a given range. Lastly, the point set of one of the candidates is projected onto the plane of the other candidate and the intersection between the projected point sets is computed. If the ratio of the points lying in the intersection is high enough, the candidate pair is considered to be a door (encircled points in Figure 3, right).

7 GRAPH GENERATION

To construct a graph encoding the building's room topology, each room is represented by a node. An edge is added for each detected door, connecting the two associated rooms. We enrich this representation with node and edge attributes. Each node is assigned a position which is set to the location of one of the involved scanners. Alternatively, the mean of the positions of all points belonging to the respective room could be used. However, this does not guarantee that the position lies within the room. Furthermore, each node is assigned an approximate room area which is computed by projecting all points into a two-dimensional grid that is aligned with the x - y -plane. The approximate room area is then estimated by computing the area of cells which contain at least one point. For each door edge, we compute the bounding box of the previously generated intersection points. The edge is then assigned this bounding box which constitutes an approximation of the door's position and shape.

8 EVALUATION

We tested our method on synthetic as well as real-world datasets. Figure 4 shows a result on synthetic

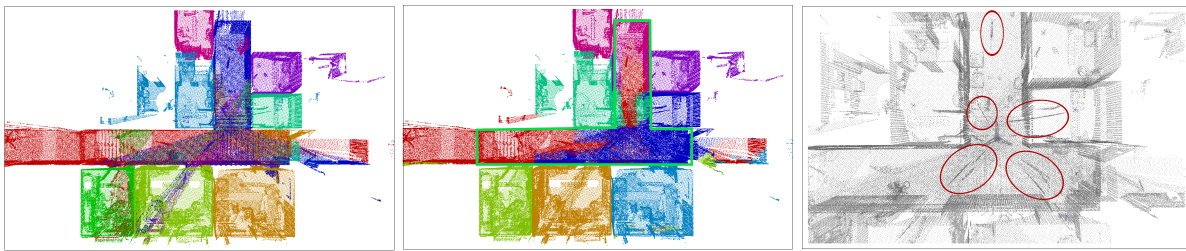


Figure 5: A failure case of our method due to a strongly non-convex room and planar artifacts in the scan data.



Figure 4: Results on synthetic data; the first picture also shows an automatic merging suggestion (red line between two scanner positions).

data. In the upper half, the initial labeling of scan positions is shown, together with an automatically computed suggestion which scan locations should be merged (indicated by the red line). The lower half shows the final topology graph as well as the estimated room areas. Figure 6 shows the results on real-world data measured in two different storeys of the same building. The upper-left pictures show the association of data points to the individual scans before merging. On the upper-right, the associations of points to merged scan positions are shown. The lower-left part shows the final labeling of the points after segmentation. The lower-right pictures show the extracted topology graph including the estimated room areas as well as the door locations and extents (blue boxes).

A failure case of our method is shown in Figure

5. The left part shows the initial association to the scanner positions. In the middle, the labeling after re-labeling is shown. Many points in the T-shaped corridor (marked with the green line) were erroneously labeled to be part of adjacent rooms. The explanation for this behaviour is twofold. Firstly, the assumption that most of the points belonging to a room can be seen from an arbitrary point within that room is violated for (strongly) non-convex rooms like the T-shaped corridor in the depicted dataset. Secondly, large planar artifacts in the input data (Figure 5, right) may lead to low visibility values in regions which should be free space.

Computation time ranges from almost instantaneous (for the lower-resolution synthetic dataset shown in Figure 4 consisting of 70000 points) to about 30 seconds (for larger datasets as shown in Figure 6 consisting of about 500000 and 600000 points, respectively).

9 IMPLEMENTATION DETAILS

For fast determination whether measured points exist near a point x on a plane p and to enable efficient computations on the GPU, we pre-compute bitmaps for each plane, providing a discretized occupancy map. Each pixel may take a continuous value in $[0, 1]$ and is initially set to 1 if at least one pixel lies within the boundary of that pixel, and to 0 otherwise. The bitmaps are subsequently smoothed using a box filter such that pixels in the vicinity of filled pixels (and thus points) are assigned values which are negatively proportional to the distance to the nearest points in the plane (the distances labeled $d(x_{p_i}, \hat{x}_{p_i})$ in Figure 2).

Using the bitmaps, we approximate the visibility function $v_p(x_1, x_2, p)$ of Section 5 for two points x_1, x_2 and a plane p . Let $\text{bitmap_value}_p(x)$ be a function of the plane p 's bitmap value which determines the pixel value at the projection of x onto p . Then the visibility function is defined as

$$v_p(x_1, x_2, p) := 1 - \text{bitmap_value}_p(x_p). \quad (7)$$

For our experiments, we set σ in Equation 2 to



Figure 6: Results on two real-world datasets. The upper-left pictures show the room associations before merging of scans belonging to the same rooms. Upper-right: Associations after the merging step. Lower-left: The room assignments after segmentation. Lower-right: The extracted graphs including detected doors and annotations for the estimated room areas.

0.05. For the plane detection, the minimum count of points needed to constitute a plane was set to a value between 200 and 2000, depending on the density of the dataset. The radius of the box filter for bitmap smoothing was chosen such that it corresponds to approximately 20 cm in point cloud coordinates. Visibility tests between pairs of points were computed on the GPU using OpenCL. The experiments were conducted on a 3.5 GHz Intel Core i7 CPU and a GeForce GTX 670 GPU with 4 GB of memory. To obtain synthetic data, we implemented a virtual laser scanner which simulates the scanning process within 3D CAD building models.

10 CONCLUSIONS AND FUTURE WORK

We presented a method for the extraction of structural building descriptions using 3D point cloud scans as the input data. Our method was evaluated using synthetic and real-world data, showing the feasibility of our approach. In most cases, the algorithm produced satisfactory results, yielding useful semantic representations of buildings for applications like navigation in point clouds or structural queries.

The usage of different visibility functionals as well as an EM-formulation to determine the parameters of the used normal distributions separately for each room label could help to improve the robustness of our method. Performance in the presence of non-convex rooms could possibly be improved by using a measure for (potentially indirect) *reachability* between points instead of visibility tests. Also, limiting the tests to a more local scope may help to overcome the identified problems. The output of our approach could be further enriched by more attributes, for instance by applying methods for the analysis of the individual room point sets after segmentation.

ACKNOWLEDGEMENTS

We would like to thank Henrik Leander Evers for the scans of Kronborg Castle, Denmark, and the Faculty of Architecture and Landscape Sciences of Leibniz University Hannover for providing the 3D building models that were used for generating the synthetic data. This work was partially funded by the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement no. 600908 (DURAARK) 2013-2016.

REFERENCES

- Ahmed, S., Liwicki, M., Weber, M., and Dengel, A. (2012). Automatic room detection and room labeling from architectural floor plans. In *10th IAPR International Workshop on Document Analysis Systems (DAS-2012)*, pages 339–343. IEEE.
- Bokeloh, M., Berner, A., Wand, M., Seidel, H.-P., and Schilling, A. (2009). Symmetry detection using line features. *Computer Graphics Forum (EG 2009)*, 28(2):697–706.
- Dempster, A. P., Laird, N. M., and Rubin, D. B. (1977). Maximum likelihood from incomplete data via the em algorithm. *JOURNAL OF THE ROYAL STATISTICAL SOCIETY, SERIES B*, 39(1):1–38.
- Duda, R., Hart, P., and Stork, D. (2001). *Pattern Classification*. Wiley.
- Kim, Y. M., Mitra, N. J., Yan, D.-M., and Guibas, L. (2012). Acquiring 3d indoor environments with variability and repetition. *ACM TOG*, 31(6):138:1–138:11.
- Koppula, H. S., Anand, A., Joachims, T., and Saxena, A. (2011). Semantic labeling of 3d point clouds for indoor scenes. In *NIPS 2011*, pages 244–252.
- Langenhan, C., Weber, M., Liwicki, M., Dengel, A., and F., P. (2012). Topological query on semantic building models using ontology and graph theory. In *EG-ICE*. TUM.
- Langenhan, C., Weber, M., Liwicki, M., Petzold, F., and Dengel, A. (2013). Graph-based retrieval of building information models for supporting the early design stages. *Advanced Engineering Informatics*.
- Nan, L., Xie, K., and Sharf, A. (2012). A search-classify approach for cluttered indoor scene understanding. *ACM TOG*, 31(6):137:1–137:10.
- Rusu, R. B., Marton, Z. C., Blodow, N., Dolha, M., and Beetz, M. (2008). Towards 3D point cloud based object maps for household environments. *Robotics and Autonomous Systems*, 56(11):927941.
- Schnabel, R., Wahl, R., and Klein, R. (2007). Efficient ransac for point-cloud shape detection. *Computer Graphics Forum*, 26(2):214–226.
- Schnabel, R., Wessel, R., Wahl, R., and Klein, R. (2008). Shape recognition in 3d point-clouds. In *WSCG 2008*. UNION Agency-Science Press.
- Verma, V., Kumar, R., and Hsu, S. (2006). 3d building detection and modeling from aerial lidar data. *CVPR 2012*, 2:2213–2220.
- Wessel, R., Blümel, I., and Klein, R. (2008). The room connectivity graph: Shape retrieval in the architectural domain. In *WSCG 2008*. UNION Agency-Science Press.
- Xiao, J. and Furukawa, Y. (2012). Reconstructing the world's museums. In *Proceedings of the 12th European Conference on Computer Vision, ECCV '12*.