

A KNOWLEDGE BASED HIERARCHICAL CLASSIFICATION TREE FOR 3D FACADE MODELING USING TERRESTRIAL LASER SCANNING DATA

Chao Luo, Gunho Sohn

GeoICT Laboratory, Department of Earth and Space Science, York University, 4700 Keele Street,
Toronto, Ontario, M3J 1P3
Canada – (cluo, gsohn)@yorku.ca

Commission I, ICWG V/ I

KEY WORDS: Knowledge, Hierarchical Classification Tree, Facade Modeling, Terrestrial Laser Scanning

ABSTRACT:

Due to high point density, accuracy and cost-effectiveness, Terrestrial Laser Scanner (TLS) do have the great advantage of providing the details of building facade as required for the production of realistic 3D city models. Thus, a significant amount of research efforts has been directed towards reconstructing building facade models using TLS data. Most of reconstruction strategies are based on geometric feature extraction, which is categorized into two groups: point-based and segmentation-based boundary extraction. However, little attention was paid on further recognizing and separating those extracted geometric features, result of which is helpful for 3D building modeling at LOD3. This paper presents an approach to recognize 3D facade features automatically from TSL data based on heuristic knowledge of geometrical and topological configuration of facade objects. All the facade knowledge is stored in a hierarchical tree, which guides the classification process. Finally, a confusion matrix is created to evaluate the classification performance.

1. INTRODUCTION

In the last years, there is an increasing demand for 3D photo-realistic city model. As the major component of cityscape, 3D building modeling is a critical work. In 3D city visualization, the same city object needs to be represented in different scale. A very important concept to describe geometric complexity of 3D building representation is Level of Detail (LOD), which allows geometry of features to be represented in different accuracy and detail (Emgard and Zlatanova, 2008). Lee and Nevatia (2003) propose a hierarchical representation of 3D building models for urban reconstruction from images. Visualization quality of the building model increases with the upgrading in LOD level. Compared with lower-level models, LOD3 goes further by representing more detailed facade geometries, such as wall, roof, door, window, sidewall, window sill .etc. Due to high point density, accuracy and cost-effectiveness, TLS data makes the building modeling at LOD3 available by providing rich geometric information of building facades.

There are two main approaches for building reconstruction from TLS data, data driven modeling and knowledge based modeling. Data driven method starts with geometric feature extraction and so it greatly depends on the quality of data acquisition, feature extraction and scene complexity. Knowledge based method heavily relies on a priori knowledge of the generic building models. The knowledge preset should be matched to given data for validating hypothesized knowledge. Thus, the derivation of geometric feature from given data is required for the knowledge based modelling, but relatively less amount of features are required compared to the data driven approach.

Three different types of features which include point, line and polygons are usually adopted as primary information for either directly deriving geometric model form data or validating hypothesized knowledge. The polygon feature can be considered as a predominant element comprising facades. However, extracted polygons using low-level vision process are not associated with semantically interpretable information (facade knowledge). Having assigned face knowledge to extracted polygon would play significant role in the inter-mediate vision process of grouping features for facade part recognition and modelling.

Our approach aims to propose a new method to recognize dominant facade elements by making polygonal featured obtained from TLS data associated with pre-specified facade knowledge for 3D facade modelling (LOD3) purpose. The proposed method starts from polygon extraction through a series of data processing including point classification, segmentation and boundary extraction. Before the polygon classification process starts, a coordinate transformation is conducted to ensure that the front facet of facade should be adjusted to orthogonal plane direction. A set of facade knowledge is heuristically pre-set for characterizing facade elements (windows, wall, wall sills, and so forth) and their topological relations. Selected characteristics include area, direction, shape index as well as depth. A hierarchical knowledge tree is applied to encode characterized facade knowledge. Finally, the knowledge tree is applied for classifying polygons which performance is evaluated by comparing with manually selected ground truth.

Section 2 discusses relevant previous works related to current research. The knowledge based hierarchical classification framework is detailedly described in Section 3. In Section 4, the

results of classification experiment are presented. Section 5 concludes the paper with discussions.

2. RELATED WORKS

Knowledge was first applied in facade reconstruction using ground view image. Most work focus on exploring the regularity of simple facade element, especially for window. Mature methods for regularity discovering either based on geometry extraction or prior information (Wang et al., 2002; Alegre and Dallaert, 2004; Muller, et al., 2007). Recently the application of rjMCMC theory on regularity discovering has attracted more and more attention (Mayer et and Reznik, 2007). Since the application of TLS data in building reconstruction is later than ground view image, little work has been done and most modeling methods are also inspired by ground image based facade reconstruction. Ripperda and Brenner (2006) propose a reconstruction strategy using a formal grammar and rjMCMC. Based on previous work (Pu and Vosselman, 2006) on automatic extraction of building feature from TLS data, Pu (2008a) further improve the extraction result by refining the feature constraints and integrating a second extraction method. Becker (2009) analyzes the structural and hierarchical relations and describes them in the form of shape grammar, from which missed parts in scanning process are estimated and refined. The above mentioned literatures work well on simple facade elements recognition and structural knowledge discovering, wall and window. However, more facade elements need to be represented in building reconstruction at LOD3. This paper aims to recognize more detailed facade elements from TLS data, such as sidewall, roof, and door based on facade knowledge.

3. METHODOLOGY

The proposed method is composed of four steps: boundary extraction of facade feature, coordinate transformation, statement of facade knowledge, knowledge-based hierarchical classification tree.

3.1 Boundary extraction of facade feature

Many algorithms on the topic of boundary generation of facade geometric feature from TLS data have been proposed (Pu, 2008b; Dold and Brenner, 2004; Bauer et al., 2005; Boulaassal et al., 2007). The boundary generation is divided into two steps, cloud point segmentation and segmentation-based outline extraction. The point cloud segmentation is the process of labelling each point with attribute, so that the points belonging to the same surface or region are given the same label (Rabbani et al., 2006). Based on the segmentation result, extracting the boundary of each facade geometric feature is available. For current research, we use a COTS software, called ClearEdge3D, to extract coarsely segmented polygons from TLS. The boundary extraction in ClearEdge3D begins with point selection of AOI (area of interest). The next step is to segment the facade into a set of planar surfaces. Furthermore, actual polygons are created to represent the previously discovered planar surfaces and then are exported as DXF format.

3.2 Coordinate transformation

We collected the point of clouds data of building facades located in Distillery District in Toronto using Riegl TLS scanner. For

current research, a sophisticated ortho-rectification of TLS data was not conducted, thus nominal directions of laser scanner and targeted facade are not co-aligned. Instead of conducting an ortho-rectification, rather simple coordinate transformation was applied. Figure 1 illustrates a situation where facade plan and a plane passing through TLS are not in parallel. One of the most important polygon characteristic that used in our classification strategy is depth, which is defined as the distance between the centre of each polygon and the scanner plane. If the scanner plane coincides with a certain axis plane, taking YoZ plane for example, depth could be simplified as the X value. Hence, to reduce the computation complexity of depth, coordinate transformation is need.

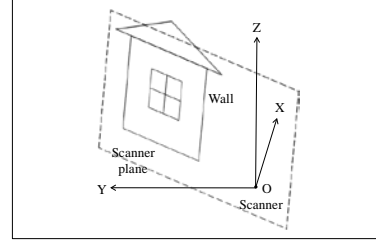


Figure 1. The dotting rectangle is the imagery scanner plane.

Coordinate transformation includes scaling, translation and rotation. In this paper, since the origin of coordinate axes doesn't translate and without scaling, coordinate transformation only involves rotation, which is done by multiplying rotation matrix and coordinate vectors. Rotation matrix is obtained by comparing the original direction and target direction. Here original direction is defined as the normal vector of the wall and target direction is set as normal vector of the YOZ plane.

However, the normal vector of the wall is not available before the wall is recognized. Here the direction of the wall is estimated by analyzing the distribution of normal vector of all polygons. Most of the situation, frontal faces of door, window, roof and columns are all parallel to the wall, and sidewall or other non-frontal surfaces of facade elements maybe have certain included angles with the wall. Moreover, the number of facade elements parallel to the wall is much more than others. Thus, two or more peaks could appear in the statistics graph of all polygons' included angle with the YOZ plane and the highest peak approximates the direction of the wall. So, average normal vector of all wall-parallel polygons is selected as the estimating normal vector of the wall.

From the original direction to target direction, normal vector of the wall rotates around Z axis and Y axis. Rotation angles are calculated by comparing the normal vector of the wall and normal vector of the YOZ plane. Equation 1 and equation 2 respectively defines the transformation matrix rotating around Y and Z axis.

$$R_Y = \begin{bmatrix} \cos\beta & 0 & -\sin\beta \\ 0 & 1 & 0 \\ \sin\beta & 0 & \cos\beta \end{bmatrix} \quad (1)$$

$$R_Z = \begin{bmatrix} \cos\gamma & \sin\gamma & 0 \\ -\sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (2)$$

where β and γ are respectively the rotation angles around Y and Z axis.

A general coordinate transformation is obtained by matrix multiplication, which is showed in Equation 3.

$$X' = R_Y * R_Z * X = \begin{bmatrix} \cos\beta & 0 & -\sin\beta \\ 0 & 1 & 0 \\ \sin\beta & 0 & \cos\beta \end{bmatrix} \cdot \begin{bmatrix} \cos\gamma & \sin\gamma & 0 \\ -\sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot X \quad (3)$$

where X is the coordinate vector before rotation and X' stands for the coordinate vector after rotation.

3.3 Heuristic Facade Knowledge

3.3.1 Facade polygonal attributes

In general, building facade usually comprises of several dominant facade features (wall, window, window sill, door, roof, side walls, etc.). There would be certain heuristic knowledge in which most of facade features are constrained for comprising facade model. The facade polygonal attributes are the information to characterize how the facade features can be inter- or intra-linked for facade model. Four attributes are discussed as follows:

Direction

Direction is defined as the included angle between the polygon and the YOZ plane, and is calculated by Equation 4

$$Angle = \arccos\left(\frac{\sqrt{n^2+p^2}}{\sqrt{m^2+n^2+p^2}}\right) \quad (4)$$

where (m, n, p) is the normal vector of a polygon.

Area

The area of a polygon is calculated by Equation 5

$$Area = \frac{1}{2} \times \sum_{i=1}^n ((y_i + y_{i+1}) \times (z_i - z_{i+1})) \quad (5)$$

where y_i and z_i is respectively the Y- and Z-values of vertexes of a polygon.

Depth

As it mentioned in section 3.2, the depth is simplified as the average x-value of all vertices in a polygon.

Shape Index

Shape Index is one of the most popular quantitative indices in the field of Ecological Geography and is used to describe and analyze landscape structure (Haines-Young and Chopping 1996). Here, the length/width ratio, a specific shape index, is used to convey how relatively rectangular a polygon appears. It is calculated by the ratio of the horizontal edge (length) and vertical edge (width) of a polygon's bounding box. The bounding box is obtained by searching the minimum and maximum value of all polygon vertices respectively in the Y axis and Z axis.

3.3.2 Facade knowledge

In this section, characteristics of seven types of facade elements are analyzed.

Wall

Wall is the remaining part after removing all protrusions (e.g. roof, window sill, and railing) and intrusions (e.g. window, door, and

sidewall). Since protrusion either locates at the top/bottom of the facade (e.g. roof), or the inside of the wall (e.g. window sill, railing) and intrusion locates at the inside of the wall, the wall appears continuous and keep coplanar in the edge area of a facade. Therefore, wall polygon covers nearly the whole facade and is the maximum polygon.

Sidewall attaching window/door

Sidewall is the side face of the wall and perpendicular to the frontal face of the wall. That is different from other intrusions like door and window, which always appears parallel to the frontal face of the wall. Thus sidewall could be separated according to angle between intrusion and frontal face of the wall. Sidewall is also viewed as attachment of door or window in some extent. Thus, there are two possible situations for sidewall, connecting to windows or doors. Since door is deeper than window, sidewall connecting to door always is apart further away the scanner plane than those connecting to window.

Window/door

Window is composed of window frame, cross bar and glass. Although these components of window are not coplanar, distances among them are smaller than the distance between them and other types of facade elements. Hence, window could be regarded as planar here. Compared with window, door usually has a greater depth. According to depth, window and door can be separated.

Wall attachment

Possible wall attachments include window sill, railing and so on. Both shape of window sill and railing look like long bars with a high ration of length and width. Since flat roof also has a high shape index value, here we only discuss the non-flat roof building. Therefore, high shape index value is a unique characteristic of wall attachment.

Roof

The greatest function of roof is protecting the building from the effects of weather. It needs protrude further than any other facade elements. So it has a smaller distance to scanner plane than other facade protrusions.

3.4 Construction of the hierarchical classification tree

Different from other supervised based classification strategies, this knowledge based method gets the classification criteria not from statistical analysis of training sets but from semantic interpretation of facade, or facade knowledge. A hierarchical classification tree is developed to store the facade knowledge.

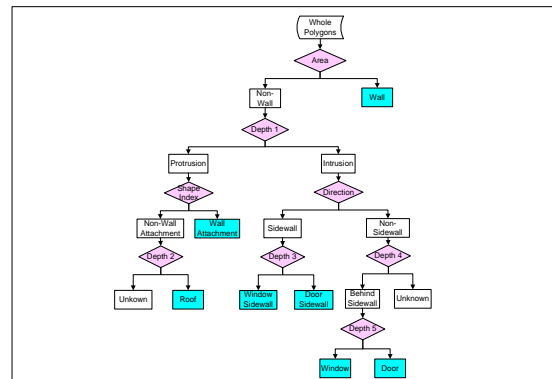


Figure 2. Hierarchical Classification Tree, magenta lozenges are judging conditions, sky-blue rectangles stand for predicted facade elements.

The knowledge based hierarchical classification tree is showed in Figure2. The classification begins with the polygons extracted from TLS data. At first, wall is obtained by searching the polygon according to area. Depth is then used to divide un-wall into protrusions and intrusions. For extrusion objects, wall attachment is firstly separated according to shape index. According to depth statistical analysis, polygon whose depth is smaller than depth of wall attachment is recognized as roof. As regard intrusion objects, sidewall is firstly separated, which is then divided into two classes based on depth. Another depth threshold is used to separate potential windows and doors, which are further classified into window and door according to difference in depth.

3.5 Thresholds selection

As it is showed in the Figure2, each non-leaf node of the hierarchical classification tree is divided into two nodes after applying a threshold. The selection of threshold is a critical issue of the classification. The following part explains how to select threshold for each non-leaf node partition. It needs to be emphasized that except for the shape index, each threshold is automatically selected through statistical analysis of polygon characteristics and greatly depends on previous classification results.

Area

This threshold is the largest area of the all polygons, which is obtained by area statistical analysis. The polygon with the largest area is wall and others fall under non-wall.

Depth1

The depth of wall is set as threshold. Polygon whose depth is greater than the threshold is classified as intrusion and the others fall under extrusion.

Shape Index

The threshold is the only one threshold value that is not obtained by statistical analysis but predefined. Since high shape index is a unique characteristic of wall attachment, wall attachment is separated from extrusion objects according to shape index. The shape index threshold is manually set as 4. Therefore, polygon whose shape index is greater than 4 is classified as wall attachment and others fall under non-wall attachment.

Depth2

The threshold is set as the average depth of wall attachment. Functioning as protection, roof extrudes further than any other protrusion objects, including wall attachment. Hence, polygon whose depth is smaller than the average depth of wall attachment is classified as roof, and the rest are still unknown.

Direction

Different from other intrusion objects, sidewall is the only object perpendicular to frontal face of the wall. Considering possible error in normal vector calculating and boundary generation, threshold is set as 10 degree. Thus, polygon has included angle greater than 10 degree with of YOZ plane is classified as sidewall. Those under 10 degree need to be further analyzed.

Depth3

Depth3 is used to separate the sidewall of the window from the one of the door. In order to get the threshold easily and exactly, a simple threshold selection method is developed, which is based on the fact that the number of window's sidewall polygon is far more than the number of door so that compared with window sidewall, door sidewall can be regarded as outlier. At first, the mean and standard deviation of all sidewall polygons' depth are calculated. According to probability theory and mathematical statistics, more than 95.4 percent of the sample data will fall within double standard deviation. Therefore, polygon whose depth is beyond right double standard deviation is classified as door sidewall and others fall under window sidewall.

Depth4

Either window or door is behind the sidewall and so average depth of sidewall is set as threshold for separating potential window and door. Polygon with depth greater than the threshold is classified behind sidewall. Others are still unknown.

Depth5

Selection of this threshold is similar to separating sidewalls attaching door from those attaching window. Mean and standard deviation of all behind sidewall polygons' depth are calculated. As door is deeper than window, polygon whose depth is beyond right double standard deviation is classified as door and others fall under window.

4. EXPERIMENT

4.1 Data

Point cloud used for testing the hierarchical classification tree is collected by RIEGL LMS-Z390i and covers the eastern facade of #2 Building of the Distillery District, which is about 23m in height and 16m in width. The TLS point number is 303, 467pts, and the point density is about 925pt/m². A photograph of this facade is presented in Figure3. Major facade elements include wall, roof, sidewall, door, window, window sill are also showed in Figure3.

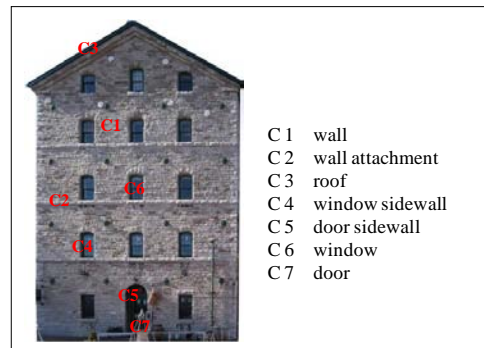


Figure 3. Photo of building facade under study.

4.2 Result

The boundary extraction work of 3D facade geometric features was done by the ClearEdge3D. 422 polygons were extracted from the input point cloud, which contains 303,467 points. Next, the

statistics graph of all polygons' included angle with the YOZ plane is obtained and polygons with 5 degree around the highest peak are selected as wall-parallel polygons. Based on the method proposed in section 3.2, transformation matrix is obtained by comparing the average normal vector of wall-parallel polygons with normal vector of YOZ plane. The transformed polygons are then gradually partitioned by applying the hierarchical classification tree.

At first, from the statistics of area of all polygons, the polygon with the largest area, $252.25 m^2$ was separated as the wall. According to depth of wall, 27.988m, protrusions and intrusions were separated. Wall attachment polygons were then taken out from extrusions since shape index of them is greater than 4. The average depth of wall attachment polygons, 27.912m, was selected for separating roof. As for intrusions, polygons with angle greater than 10 degree were classified as sidewall. Polygons with depth greater than the average depth of side wall polygons, 28.121m, were separated as potential window and door. According to the double standard deviation method, which mention in section 3.5, 28.688m and 28.345m were respectively to separating window and door as well as window sidewall and door sidewall. Finally, 202 polygons are recognized and detailed classification result is showed in Figure 4.

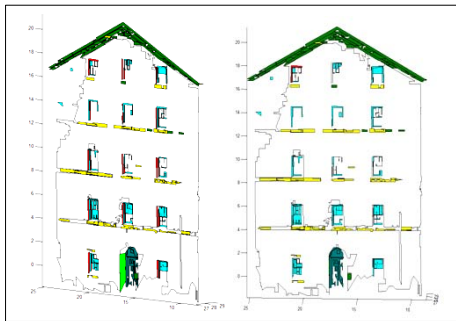


Figure 4. Classification result by applying the hierarchical classification tree. Each element is filled in a specific color.

4.3 Quality Analysis

Overall classification accuracy, precision and recall are used to evaluate the classification performance. At first, actual points of each type of facade element are manually selected from the original point cloud as reference data for comparison of ground truth and classification result. Then the actual points and predicted polygons are displayed together within the same window. Visual interpretation is applied to check whether each polygon covers the point area. Evaluation of window detection result is showed in Figure5. Based on the visual comparison for all classes, a confusion matrix is created. The confusion matrix for the verification dataset together with commission and omission accuracies is given in Tables 1. In Table1, each row represents the instances in a predicted class, and each column represents the instances in an actual class. From the Table1, we can get that the overall classification accuracy is 95.54%, which is calculated as the sum of correct classified polygons divided by the total number.

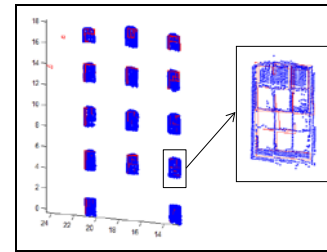


Figure 5. Superimposition of actual points (blue) and predicted polygons (red).

The commission error reflects the probability that, given a polygon from a certain predicted class, it does not belong to the same class in the reference data. And the omission error measures the probability that, given a polygon of the reference data, it has not been correctly classified in the prediction class. In short, commission is a measure of the exactness, whereas recall is a measure of the omission. The lower these two values, the more excellent the classification performs.

		Reference								
		Wall	Roof	Window Sill	Window Sidewall	Door Sidewall	Window	Door	Total	Commission error (%)
predicted	Wall	1	0	0	0	0	0	0	1	0
	Roof	1	39	4	0	0	0	0	44	11.36
	Window Sill	1	1	39	0	0	0	0	41	4.87
	Window Sidewall	0	0	0	41	0	0	0	41	0
	Door Sidewall	0	0	0	0	1	0	0	1	0
	Window	2	0	0	0	0	59	0	61	3.28
	Door	0	0	0	0	0	0	13	13	0
	Total	5	40	43	41	1	59	13	202	
Omission error (%)	80	2.5	9.77	0	0	0	0			

Table 1. Confusion matrix.

For commission, values of all elements are lower than 0.15 and four classes are even low as zero. The low commission value means that most of detected polygons correctly fall down their actual class. No matter whether all the polygons of a class have

been detected, the detected polygons are strongly reliable for 3D modeling. In terms of omission, except for wall, values of all other are lower than 0.1. The omission value of the wall is high as 0.8 but the high omission doesn't affect the quality of wall detection

due to that 4 wrongly classified actual wall polygons are no more than 0.1 square meters, which is further smaller than size of the detected wall, whose area is about 250 square meters. From the overall high classification accuracy, low commission and omission, it is obvious that the knowledge based hierarchical classification tree is effective and exact.

5. CONCLUSION AND FUTURE WORK

In this paper we present a knowledge-based hierarchical classification strategy for 3D facade modeling using TSL data. The method starts from boundary generation of facade geometric feature from TLS data using Clearedge3D. The parameters, such as area, depth, direction as well as shape index, are used to describe facade knowledge, including characteristics of each facade element and interrelationship among them. Depth is first put forward for the facade element classification but it plays the most important role in knowledge description. Then a hierarchical classification tree is developed to store the facade knowledge. The classification begins with the whole transformed polygons and then each non-leaf node is divided into two groups according to corresponding threshold until no non-leaf node is found. The threshold selection is based on statistical analysis so that they depend heavily on previous classification results. Finally, overall classification accuracy is calculated to evaluate the overall classification performance; commission and omission are used to evaluate the exactness and completeness. The experiment proves that this classification strategy is effective. However, much work remains to be done in the future. First of all, more characteristic such as topology, position, height will be applied to describe facade knowledge. Furthermore, investigations on utilizing the classification result in city modeling at LoD3 will be carried on.

ACKNOWLEDGEMENT

This research is financially supported by the Chinese State Scholarship Fund and GEOIDE.

REFERENCE

- Alegre, F. and Dallaert, F., 2004. A probabilistic approach to the semantic interpretation of building facades. In: *International Workshop on Vision Techniques Applied to the Rehabilitation of City Centres*, pp. 1–12.
- Bauer, J., Karner, K., Schindler, K., Klaus, A. and Zach, C., 2003. Segmentation of building from dense 3D point clouds. In: *Proceedings of 27th Workshop of the Austrian Association for Pattern Recognition*, pp. 253–258.
- Becker, S., 2009. Generation and application of rules for quality dependent facade reconstruction. *ISPRS Journal of Photogrammetry and Remote Sensing*, 64(6), pp. 640–653.
- Boulaassal, H., Landes, T., Grussenmeyer, P. and Tarsha-Kurdi, F., 2007. Automatic segmentation of building facades using terrestrial laser data. In: *Proceedings of the ISPRS Workshop on Laser Scanning 2007 and SilviLaser 2007*, Espoo, Finland, IAPRS vol. 36, part 3/W52, pp. 65–70.
- Dold, C. and Brenner, C., 2004. Automatic matching of terrestrial scan data as a basis for the generation of detailed 3D city models. In: *International Archives of Photogrammetry and Remote Sensing*, Vol. 36, Part B3, Proceedings of the ISPRS working group III/6, Istanbul, pp. 1091–1096.
- Emgard L. and Zlatanova, S., 2008. Implementation alternatives for an integrated 3D information model. In: *Advances in 3D Geoinformation Systems*, Springer-Verlag, Heidelberg, pp. 313–330.
- Haines-Young R. and Chopping M., 1996. Quantifying landscape structure: a review of landscape indices and their application to forested landscapes. *Progress in Physical Geography*, 20(4), pp. 418–445.
- Lee, S. C. and Nevatia, R., 2003. Interactive 3d building modeling using a hierarchical representation. In: *International Workshop on Higher-Level Knowledge in 3D Modeling and Motion Analysis*, IEEE Computer Society, pp. 58–65.
- Mayer, H., Reznik, S., 2007. Building facade interpretation from uncalibrated wide-baseline image sequences. *ISPRS Journal of Photogrammetry and Remote Sensing*, 61(6), pp. 371–380.
- Muller P., Zeng G., Wonka P. and Gool L. V., 2007. Image-based procedural modeling of facades. In: *Proceedings of ACM SIGGRAPH 2007 / ACM Transactions on Graphics*, 26(3) pp. 85
- Pu, S. and Vosselman, G., 2006. Automatic extraction of building features from terrestrial laser scanning. In: *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. 36, Part 5, Dresden, Germany
- Pu, S., 2008a. Automatic building modelling from terrestrial laser scanning. *Advances in 3D Geoinformation Systems*, Ed. by Oosterom, P., et al., Springer, pp. 147–160.
- Pu, S., 2008b. Generating building outlines from terrestrial laser scanning. In: *ISPRS 2008: Proceedings of the XXI congress: Silk road for information from imagery*, Beijing, China, pp. 451–455.
- Ripperda, N. and Brenner, C., 2006. Reconstruction of facade structures using a formal grammar and rjMCMC. *Pattern Recognition*, Ed. by Franke, K., et al., Springer, pp. 750–759.
- Rabbani T., Van den Heuvel, F. and Vosselman, G., 2006. Segmentation of point clouds using smoothness constraint. In: *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. 36, part5, Dresden, Germany, pp. 248–253
- Wang, X., Totaro, S., Taillandier, F., Hanson, A. and Teller, S., 2002. Recovering facade texture and microstructure from real-world images. In: *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. (34) 3A, pp. 381–386.