LEVELS OF DETAIL IN 3D BUILDING RECONSTRUCTION FROM LIDAR DATA

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ABSTRACT:

3D models of buildings are useful for many applications such as urban planning and environmental simulation, cartography, tourism and mobile navigation. Automatically generating building models in the form of 3D CAD representation is the major part of city modeling and a challenge for many researchers. Airborne laser-scanning (ALS) results into high-quality geometrical information about the landscape. It is suitable for the reconstruction of 3D objects like buildings because of its high density and geometrical accuracy. In this paper a novel approach is proposed for automatically generating 3D building models based on definition of Levels of Detail (LOD) in the CityGML standard. Three levels of detail are considered in this paper. In the first LOD (LOD0), the Digital Terrain Model extracted from LIDAR data is represented. For this purpose the Digital Surface Model is filtered using geodesic morphology. A prismatic model containing the major walls of the building is generated to form the LOD1. The building outlines are detected by classification of non-ground objects and the building outlines are approximated by two approaches; hierarchical fitting of Minimum Boundary rectangles (MBR) and RANSAC based straight line fitting algorithm. LOD2 is formed by including the roof structures into the model. For this purpose, a model driven approach based on the analysis of the 3D points in a 2D projection plane is proposed. A building region is divided into smaller parts according to the direction and the number of ridge lines, which are extracted using geodesic morphology. The 3D model is derived for each building part. Finally, a complete building model is formed by merging the 3D models of the building parts and adjusting the nodes after the merging process.

1 INTRODUCTION

3D building reconstruction is a challenging problem addressed by many researchers. Since airborne LIDAR data appeared as a new data source in remote sensing and photogrammetry many attempts were made to model buildings using LIDAR data. LIDAR combined with aerial images was e.g., used for building reconstruction by (Haala and Anders, 1997, Rotensteiner and Jansa, 2002). The LIDAR data is employed for segmentation of planar faces and the aerial image is involved to improve the quality of edge segments. The combination of LIDAR data and existing ground plans was e.g., proposed by (Vosselman and Dijkman, 2001). They employed two strategies for building reconstruction. The first strategy is based on detection of intersection lines and height jump edges between planar faces. In second strategy, a coarse 3D model is refined by analyzing the points that do not fit well to the coarse model. The first approach which used only LIDAR data for building reconstruction was presented by (Weidner and Förstner, 1995). They mainly used two types of models; simple parametric models for buildings with rectangular ground plans and prismatic models for complex buildings. (Maas, 1999) developed another model driven approach based on analysis of invariant moments of the segmented regions to model buildings in LIDAR image. He assumes that buildings consist of certain structures such as gable roofs. A prismatic building model based on edge detection is extracted in (Alharthy and Bethel, 2002). However, the algorithm is devised for buildings with rectangular shapes and flat roofs only. A segmentation based approach is proposed by (Rottensteiner and Briese, 2002) to find planar regions which figure out a polyhedral model. Another segmentation approach that uses a TIN structure for the LIDAR surface model is proposed by (Gorte, 2002). Segments are created by iterative merging triangles based on similarity measurements. Finally, the segmented TIN structures are transformed into a VRML model for visualization.

In this paper a new method is proposed for generating 3D building models in different levels of detail. They follow the standard definition of the City Geography Markup Language (CityGML) described in (Kolbe et al., 2005). The CityGML defines five levels of detail for multi-scale modeling: LOD0 – Regional model contains 2.5D Digital Terrain Model, LOD1 – Building block model without roof structures, LOD2 – Building model including roof structures, LOD3 – Building model including detailed architecture, LOD4 – Building model including interior model.

Algorithms for producing the first three levels are explained in this paper. According to above categorization, the first LOD corresponds to the digital terrain model. An approach based on the filtering of the non-ground regions uses geodesic reconstruction to produce the DTM from LIDAR DSM (Arefi and Hahn, 2005, Arefi et al., 2007b). The LOD1 level contains a 3D representation of buildings using prismatic models, thus the building roof is approximated by a horizontal plane. Two techniques are implemented for approximation of the detected building outline which are hierarchical fitting of Minimum Bounding Rectangles and RANSAC based straight line fitting and merging (Arefi et al., 2007a). To form the third level of detail (LOD2), a projection based approach is proposed for reconstructing a building model with roof structures. The algorithm is relatively fast, because the 2D data are analyzed instead of 3D data, i.e. lines are extracted rather than planes. The algorithm begins with extracting the building ridge lines. According to the location and orientation of each ridge line one parametric model is generated. The models of the building parts are merged to form the complete building model.

The paper is organized as follows: Section 2 gives an overview on the proposed algorithm for generating 3D models from LIDAR point clouds in three LOD. DTM generation from LIDAR data is explained in section 3. Section 4 explains building outlines are detected and approximated to produce second LOD. In section 5, the idea of modeling based on projecting 3D data into a 2D plane and generating the LOD2 model is explained and finally, in section 6, the achieved quality of the reconstructing buildings is discussed.

2 PROPOSED ALGORITHM FOR 3D BUILDING MODEL GENERATION IN THREE LEVELS OF DETAIL

Figure 1 presents the proposed work flow for automatic generation of building models. The process begins with separating non-ground from the ground regions by hierarchical filtering using geodesic reconstruction. A DTM is produced by interpolating the gaps obtained by the filtering process. The result represents the first LOD, i.e. LOD0. The approach continuous with extracting building regions from the ALS range data. A segmentation and classification algorithm groups and classifies the laser range pixels into building, vegetation and other classes. Next, the building outlines are detected and approximated to reduce the number of boundary pixels to some significant nodes. After estimating an average height for the building, a prismatic building model is generated to form the second LOD, i.e. LOD1. Projection based analysis of the LIDAR data is proposed for 3D building reconstruction to form the LOD2. The algorithm uses geodesic morphology for line detection and a 2D model driven technique for building reconstruction.

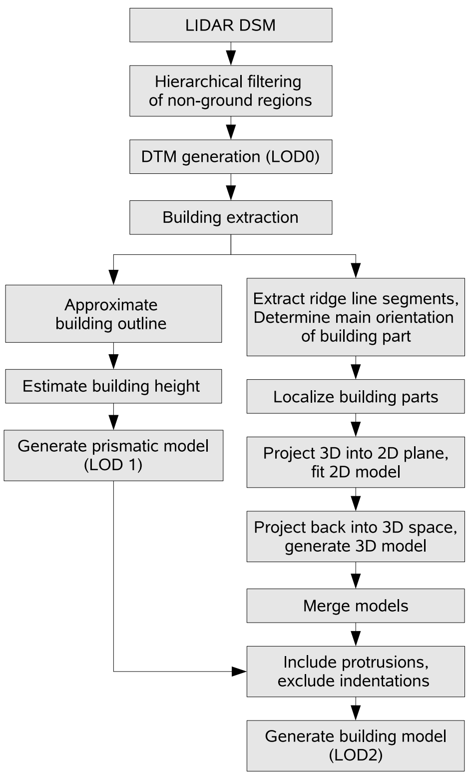
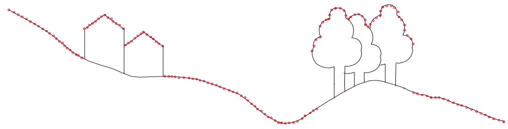


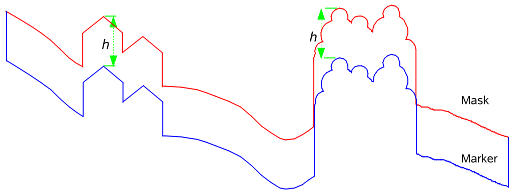
Figure 1: Work flow for automatic 3D building reconstruction

3 AUTOMATIC DTM GENERATION – LOD0

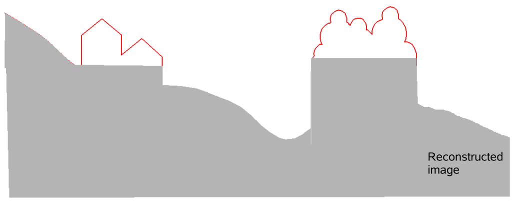
A hierarchical approach for filtering of the non-ground regions in LIDAR data and generating digital terrain models has presented in (Arefi and Hahn, 2005, Arefi et al., 2007b). Image reconstruction based on geodesic dilation is the core of this algorithm which is proposed by (Vincent, 1993). The image reconstruction is achieved by applying geodesic dilations until stability is reached (Jähne et al., 1999). The idea of image reconstruction is shown in figure 2. A profile of some non-ground objects located on an uneven surface is shown in figure 2(a). Laser points (red dots) are overlaid to the profile. The only input to generate image reconstruction is the height difference h shown in figure 2(b). The result of geodesic image reconstruction is displayed in figure 2(c). The reconstructed image is subtracted from the original im-



(a) Profile representing the ground (black color) and the location of the laser points (red dots)



(b) $mask$ and $marker$; $marker$ = $mask$ - h except pixels at the boundary of the image when $marker$ =$mask$



(c) Geodesic image reconstruction of (b)

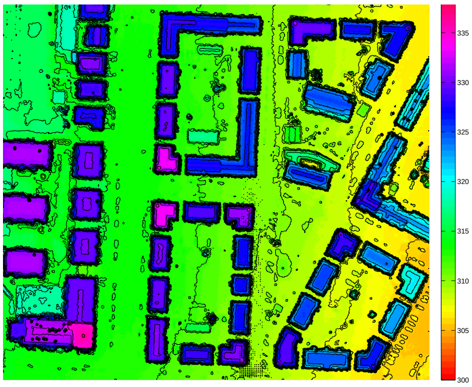
(d) $nDSM$ of (c)

Figure 2: Geodesic image reconstruction by selecting a $marker$ image by subtracting h as offset value from the $mask$ image.

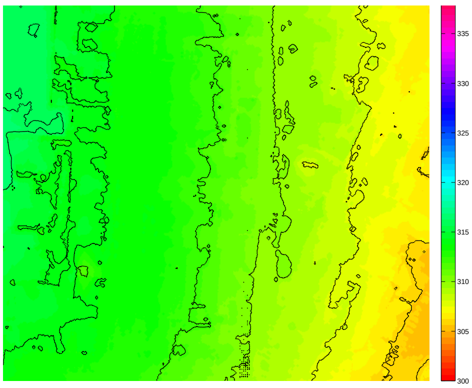
age to shape the normalized DSM 2(d). In this initial nDSM or nDSM0 small hills may incorrectly be included. To avoid this problem the initial nDSM of non-ground regions is evaluated by a feature criterion that highlights jumps. The surface normal or the local range variation (LRV) defined by the difference between dilated and eroded LIDAR image in 3×3 local windows can be used as features. Thresholding and connected components analysis leads to potential non-ground regions. The boundary pixels of these regions are evaluated by these features and the regions with height jumps are classified as non-ground. A sequence of marker images, provided by different offsets h, are used hierarchically to detect high as well as low non-ground objects. After separating the ground and non-ground pixels in the LIDAR data the gaps are filled using interpolation to get the DTM (LOD0).

There are some advantages on filtering of the laser images using geodesic image reconstruction:

- The process is not sensitive to the size of the objects to be filtered. Spacious as well as small buildings can be filtered using this approach.
- Contrary to standard morphological processing, for which proper structuring elements have to be defined this is not the case in this process. In geodesic dilation the marker image is dilated by an elementary isotropic structuring element.
- Another benefit is that, the geodesic image reconstruction does not effect ground pixels. Therefore the normalized DSM can be simply segmented using a threshold value of zero.
- The filtering approach based on geodesic dilation is relatively fast. In many cases even in hilly regions the filtering can be implemented with a single marker image. A marker image which represents the minimum height value of the mask image except pixels at the boundary when $marker = mask$ (Arefi et al., 2007b) can be used.



(a) last pulse laser image plus contour lines overlaid on it



(b) DTM generation result (LOD0) plus contour lines superimposed on it

Figure 3: Generation of digital terrain model by hierarchical filtering of non-ground objects

4 BUILDING OUTLINE DETECTION AND APPROXIMATION FOR GENERATING 3D PRISMATIC MODEL – LOD1

The normalized DSM shown in figure 2(d) contains buildings as well as vegetation pixels and other 3D objects might be also present in the data. Classification of the regions is carried out rule based using geometric and other region properties. Size of the regions, vegetation index based on first and last pulse range data and variance of the surface normals have been employed in rule based classification to separates building and vegetation regions. To model the second level of detail the extracted building outline is simplified to a polygon which includes only few significant points such as corners. For this purpose two methods are employed: fitting a rectilinear polygon by iterative fitting of minimum bounding rectangles (MBR) and straight line fitting and merging based on RANSAC (Arefi et al., 2007a). The first method is simple and relatively fast to find the best rectilinear polygon but is only applicable on rectangular polygons. First

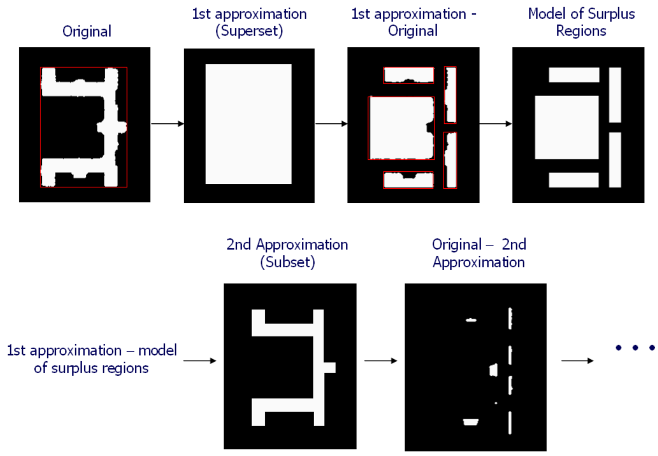


Figure 4: Iterative process of MBR for building outline approximation

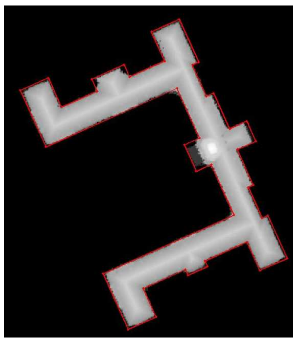
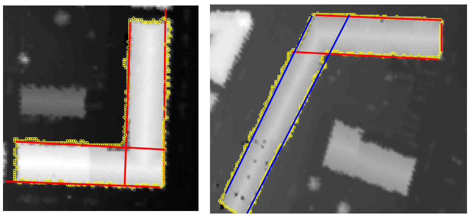


Figure 5: Building approximation result

the main orientations of the building edges are determined using a Hough transform. The iterative process of applying MBR's is shown in figure 4. The process stops if the remaining unmodeled details are neglectable. A result of such a MBR approximation is shown in figure . If the analysis in Hough space indicates that there is more than one main orientation (cf. 6) the second technique is used. The example shown in figure illustrates that the left building has a single main orientation represented by the red lines and the right building has two main orientations represented by red and blue lines. Accordingly, outline polygons are extracted and approximated with MBR or the RANSAC method.
To generate the 3D model from 2D polygons the z component of the polygon nodes is extracted from the DTM and averaged. A representative height of the building is found by averaging the heights of the LIDAR points inside the boundary polygon. Next, the polygons relating to the walls and floor of each building are formed. All 3D polygons are overlaid on DTM to create LOD1 representation.



(a) One-orientation building (b) Two-orientation building

Figure 6: Building main orientations; The yellow points represents the building outline and the red and the blue lines are the lines found by Hough transform.

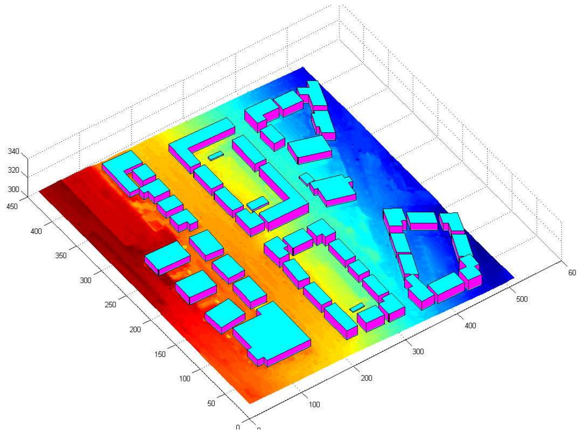


Figure 7: 3D prismatic model overlaid on digital terrain model creates the LOD1 representation

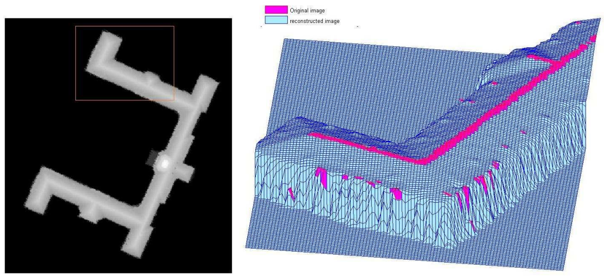
5 A NOVEL APPROACH FOR BUILDING RECONSTRUCTION BASED ON PROJECTION BASED ANALYSIS OF 3D POINTS – LOD2

The concept of our projection based building reconstruction approach is as follows. Geodesic image reconstruction with a very small height difference (cf. Figure 2) captures ridge points and roof outlines very reliably. This allows to deduce the main orientation of buildings or building parts and a corresponding buffer zone (cf. Figure 10(a)). Next, a cuboid region which covers the building or building part is extracted. The spatial direction is used to define a 3D to 2D projection of the cuboid region. All 3D laser points included in the cuboid are projected onto a 2D projection plane, which is one of the planes of the cuboid. The projection of all laser points of the 3D volume results in point accumulations in the 2D projection. The cumulation of points corresponds to the main building shape in terms of a profile which represents the roof and typically the vertical walls. In our approach only a limited number of roof models is taken into account which are flat, hipped and gabled roofs. Figure 10 shows an example of a gable roof for a part of a building. Robust line fitting approximates the profile by straight line segments from which a polygon with the roof and the vertical walls is derived. This automatically eliminates any details of the shape the building or building part. By extruding the extracted 2D information to 3D along the normal to the projection plane a 3D model of the building or building part is determined. The 3D model of the whole building is obtained by intersecting the models of its parts. The result is considered as the LOD2 representation. Refinement to greater detail follows the same conceptual idea. Instead of working with all data of the cuboid in one projection plane, a sequence of section planes is used which accumulate the respective part of the points of the cuboid.

The proposed approach for generating 3D building models consists of the following steps:

5.1 Extract ridge line and determine main orientation

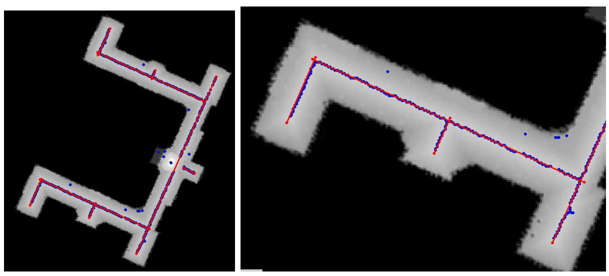
It begins with image reconstruction by geodesic morphology to extract the pixels of the highest part of the building segment. A small height offset value, e.g., $0.2m$ is chosen for this purpose. As outcome all pixels that belong to the local peaks and their neighborhood are detected as shown in figure 8(b). For flat roofs the detected pixels represent the complete roof region. The region segments obtained by labeling connected components are classified into flat roof and ridge points using Gaussian curvature and surface normal as features for the classification. The number of extracted points in this step depends on the selected offset value and the inclination of the roof face. Some other regional maxima are also detected in this step (cf. Figure 8(b)). Next, straight



(a) Range image (b) Roof top pixels; Difference between original image and reconstructed image is represented by red points

Figure 8: Determination of roof top

line segments are extracted with RANSAC from the ridge points. The orientation of the ridge line segments are calculated and verified by the orientation of the boundary lines (section 4). Since in most cases the ridge lines are parallel or perpendicular to the building edges, the orientation of the ridge is compared with the main orientation of the building. If the deviation angle (ξ) between the ridge line and the main orientation is less than, e.g. $\pm 5°$, the ridge line is rotated around its center of gravity with the value of ξ. The orientation for building parts with flat roofs is calculated based on the minimum bounding rectangle for the roof outline. Figure 9 shows the points classified as ridge points and the RANSAC lines superimposed on the original LIDAR image. Ridge points shown in blue in this figure are outliers of the RANSAC process or lines which are not approved because not enough inliers are found.



(a) Ridge points and ridge lines (overall view) (b) Ridge points and ridge lines (detail)

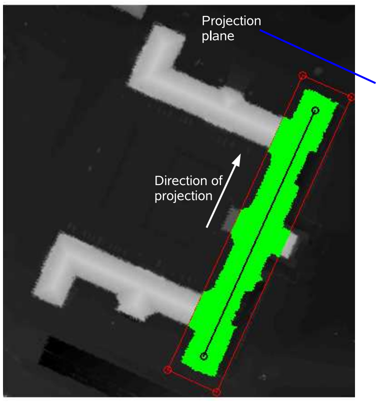
Figure 9: Classified points as ridge points (blue points) and lines fitted by RANSAC (red lines) superimposed on LIDAR image

5.2 Localization of the building parts

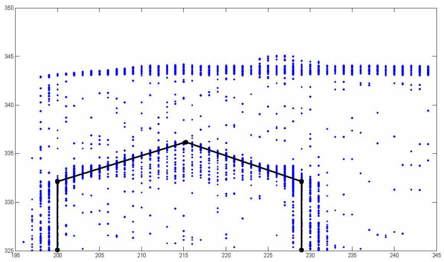
For a rectangle parallel (or perpendicular) to the main orientation the points located inside it are extracted using the point-in-polygon algorithm. This step is necessary for buildings containing more than one part. A rectangle parallel to the main orientation (parallel to ridge line) is created. A rectangle is defined around the ridge line with equal distances of the edges to the ridge line. The limits of the rectangle are selected in this way that detected building pixels (cf. Section 4) are all included. In figure 10(a), the rectangle is displayed by red lines and the localized points are shown by green dots. The direction of the projection, which is equal to the orientation of selected ridge line (black line) is shown by the white arrow.

5.3 Project 3D into 2D plane and fit 2D model

The localized points are projected which is defined by a vertical plane. According to the type of the roof which has been determined by classification before, a 2D model is fitted to the projected points. For flat roofs just two vertical lines and a horizontal line connected to the top of them is fitted. For roofs with a ridge line, a model consisting of two vertical lines as well as two sloped lines which intersect at the ridge are fitted. Figure 10 illustrates the projected points with blue points and the 2D model fitted to the data set with black lines.



(a) Localization of building part



(b) Fit of 2D model to projected data

Figure 10: Principle of projection based modeling

5.4 From 2D to 3D space – LOD2

The 2D model is converted to 3D by extruding it orthogonally to the projection plane. The 3D model comprises four walls plus one to four roof planes: a horizontal plane in case of a flat roof, two inclined planes in addition to two vertical triangular planes for a gabled roof and four inclined planes for a hipped roof. After reconstructing 3D models for all building parts, they are combined to form the overall 3D model of the building. Figure 11 displays a building model produced by merging 8 building parts. The 8 ridge lines leads to 8 parametric building models with hipped roofs. After combining the models an overall 3D model is provided. For nodes of the building parts which have to be merged because they represent e.g. the same corner of the building the average value is determined. Figure 11 shows that, there is a 3D segment which is not modeled and that is above the entrance of the Stuttgart new castle. A proper model for this area would be a dome which not taken into account in our approach. Further a flat roof model is created and added to the 3D building model as can be seen in figure 13. As shown in figure 14, edge refinement is employed for not rectangular building parts . The model contains two parametric models, the gray points represents the points above the fitted model and the colored ones are the points below the model. As shown in figure 14(b) two nodes should be refined after combination. The distances between the original LIDAR data points to each edge line are calculated and the edge is extended (or shortened) from both sides to the last point having distance less than a certain threshold. Nodes generated from more than one vertex the average value is chosen. 2D information

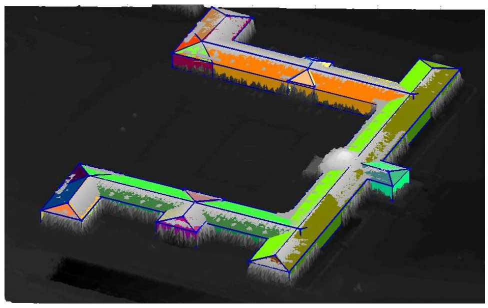


Figure 11: 3D Building Model

about the building boundaries comprising protrusions and indentations can be extracted from the result generated in LOD1. The nodes of the protrusions and indentations are determined from the approximated polygon and the corresponding planes on the roof (either flat or inclined ones) are adapted.

The figure 12 displays an approximation result for our building which is superimposed on original image as red color polygon. The reconstructed building model is overlaid on image in blue color. The figure shows that the 2D outline of the approximation result and 3D overall outline of the building model almost fit together. In this figure, one indentation part and two protrusion parts are available which should be included or excluded from the model. Indentation is a low height building model which is modeled using a cuboid. Two protrusions are excluded using information extracted from approximated outline. The inclination of the building roofs after including protrusions are adapted in a final step.

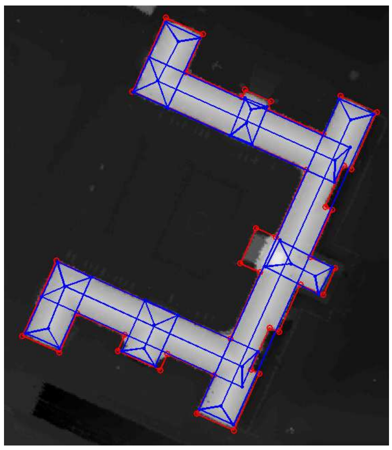


Figure 12: Approximation of building outline (red polygon) and the reconstruction result (blue polygons) overlaid on original image

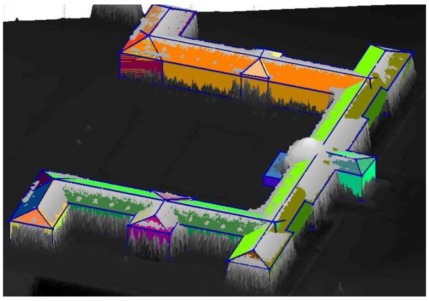
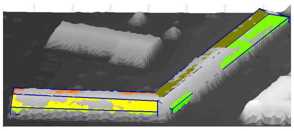


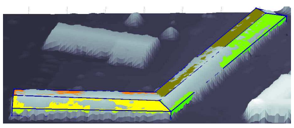
Figure 13: 3D Model merging protrusion and excluding indentations

6 DISCUSSION

In this paper an automatic approach for reconstructing models in three levels of detail is proposed based on LIDAR data. The modeling approach deals with buildings which are formed by combination of flat roof, gabled roof as well as hipped roof segments. The example used in the previous section to illustrate our developed algorithms shows that our concept for building reconstruction works quite well. A strength of this projection based approach is its robustness and that it is quite fast because projection into 2D space reduce the algorithmic complexity significantly.



(a) Building reconstruction before adjusting the nodes



(b) Building reconstruction after adjusting the nodes

Figure 14: Another example for projection based building modeling

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REFERENCES

Alharthy, A. and Bethel, J., 2002. Heuristic filtering and 3d feature extraction from lidar data. IAPRS International Archives of Photogrammetry and Remote Sensing and Spatial Information Sciences 34(3A), pp. 23–28.

Arefi, H. and Hahn, M., 2005. A morphological reconstruction algorithm for separating off-terrain points from terrain points in laser scanning data. In: Proceedings of the ISPRS Workshop Laser scanning, Enschede, the Netherlands.

Arefi, H., Engels, J., Hahn, M. and Mayer, H., 2007a. Approximation of building boundaries. In: Urban Data Management Systems (UDMS) Workshop, Stuttgart.

Arefi, H., Engels, J., Hahn, M. and Mayer, H., 2007b. Automatic dtm generation from laser-scanning data in residential hilly area. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences. Joint Workshop "Visualization and Exploration of Geospatial Data", June 27-29, 2007, Stuttgart, Germany.

Gorte, B., 2002. Segmentation of tin-structured surface models. In: Symposium on Geospatial Theory, Processing and Applications; Working Group IV/6; Ottawa, Canada; July 8 - 12, Joined Conference on Geospatial Theory, Processing and Applications.

Haala, N. and Anders, K.-H., 1997. Acquisition of 3d urban models by analysis of aerial images, digital surface models and existing 2d building information, spie proceedings. In: SPIE Conference on Integrating Photogrammetric Techniques with Scene Analysis and Machine Vision III, Vol. 3072, pp. 212–222.

Jähne, B., Haussecker, B. and Geissler, P., 1999. Handbook of Computer Vision and Application, Volume II, Signal Processing and Pattern Recognition. Academic Press.

Kolbe, T. H., Groeger, G. and Pluemer, L., 2005. Citygml interoperable access to 3d city models. In: F. E. Oosterom, Zlatonova (ed.), Proceedings of International Symposium on Geo-information for Disaster Management, 21-23 March 2005 in Delft, Springer Verlag.

Maas, H.-G., 1999. Fast determination of parametric house models from dense airborne laserscanner data. ISPRS Workshop on Mobile Mapping Technology, Bangkok, Thailand.

Rotensteiner, F. and Jansa, J., 2002. Automatic extraction of buildings from lidar data and aerial images. In: International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. 34number 4, ISPRS Technical Commission IV Symposium: Geospatial Theory, Processing and Applications, pp. 569–574.

Rottensteiner, F. and Briese, C., 2002. A new method for building extraction in urban areas from high-resolution lidar data. IAPRS International Archives of Photogrammetry and Remote Sensing and Spatial Information Sciences 34(3A), pp. 295–301.

Vincent, L., 1993. Morphological grayscale reconstruction in image analysis: Applications and efficient algorithms. IEEE Transactions on Image Processing 2, pp. 176–201.

Vosselman, G. and Dijkman, S., 2001. 3d building model reconstruction from point clouds and ground plans. In: International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 3/W4, Vol. 34, Annapolis, MA, USA, pp. 37–44.

Weidner, U. and Förstner, W., 1995. Towards automatic building extraction from high resolution digital elevation models. ISPRS Journal of Photogrammetry and Remote Sensing 50, pp. 38–49.