Improving the Realism of Existing 3D City Models

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Abstract

Within the paper, a novel approach for the reconstruction of geometric details of building façades is presented. It is based on 3D point clouds from terrestrial laser scanning. By a segmentation process, the approximate boundaries of the windows are detected and a cell decomposition of the façade is created. A classification of the cells determines a symmetric window arrangement of maximum likelihood.

Introduction

The acquisition of 3D city and landscape models has been a topic of major interest and a number of algorithms have become available both for the automatic and semiautomatic data collection. Usually based on aerial data like stereo images or LIDAR, these algorithms provide an efficient way for generating area covering urban models. Although such building models already allow a number of applications, further quality improvement is required for some scenarios. A realistic visualization from a pedestrian's viewpoint is one example where the quality and amount of detail needs to be improved. This can be achieved e.g. by the additional use of terrestrial images mapped against the building façades [1] (see figure 1). Real world imagery, however, is only feasible to a certain degree. Balconies, ledges or windows e.g. will not appear realistically if oblique views are generated. This situation can only be slightly improved if rendering techniques like bump or displacement maps are used [2]. Thus, a geometric refinement of the building façades is necessary.

Tools for the generation of polyhedral building models are either based on constructive solid geometry (CSG) or a boundary representation (B-Rep) approach. In the following section, the pros and cons of both approaches will be discussed. This will motivate the use of cell decomposition as our favored form of solid modeling in order to reconstruct the façade geometry of coarse building models.

Fig. 1. 3D city model of Stuttgart with terrestrially captured façade textures.

Solid Modeling

The buildings of 3D city models are generally reconstructed and represented as 3D solids. There exist a number of theoretical concepts for solid modeling, the most prominent being boundary representation (B-Rep) and constructive solid geometry (CSG).

In boundary representation, the geometry of an object is defined by its surface boundary, which consists of vertices, edges and faces. A reconstruction from airborne laser scanning data can e.g. be directly generated by triangulating the 2.5D point clouds. However, the architectural characteristics of buildings like right angles and parallel faces are not captured in such an approach. Therefore, a number of reconstruction algorithms first extract planar regions of appropriate size in a segmentation step. A polyhedral building model is then constructed from the resulting segments by intersection and step edge generation. Although numerous such approaches exist, an implementation that produces topological correct boundary representations is difficult [3]. This is additionally aggravated if geometric constraints, such as meeting surfaces, parallelism and rectangularity need to be guaranteed.

Regularization conditions are easier met if constructive solid geometry is used [4]. Simple primitives are combined using Boolean operators such as union, intersection and difference. This way of modeling objects is more intuitive than specifying boundary surfaces directly. A CSG representation is also always valid as the combination of Boolean operations yields topologically correct objects. Because simple primitives allow robust parameter estimation for error prone measurements, the CSG concept has been very popular for building reconstruction. If supplied with an appropriate set of primitives, even complex buildings can be constructed. However, the visualization and analysis of the data requires a transformation into boundary representation. This so-called boundary evaluation is conceptually not difficult, but problems of numerical precision and unstable intersection algorithms can prohibit the generation of a valid object topology [5].

In order to overcome the aforementioned problems, we demonstrate the applicability of cell decomposition as a tool for 3D façade reconstruction. Cell decomposition is a general form of spatial-partitioning representations which subdivide space into a set of simple primitives. A complex object is constructed by a set of adjoining primitives that are glued together. The gluing operation is a restricted form of a spatial union operation. As the primitives are not allowed to intersect one another, the implementation of algorithms does not suffer numerical instabilities.

In contrast to the constructive nature of the CSG representation, cell decomposition is generally used as an auxiliary representation for analytical computations [6]. However, we will demonstrate in the following chapters that cell decomposition can be an effective tool for the automatic reconstruction of topological correct façade models from terrestrial LIDAR point clouds.

Façade Refinement by Terrestrial LIDAR

For a number of applications, 3D city models extracted from aerial data are sufficient. Some tasks, however, require an increased amount of geometric details for the respective 3D building models. One example is the realistic visualisation as seen from a pedestrian viewpoint. As already mentioned, this can be achieved by mapping terrestrial images or displacement maps against the façades. These techniques have their limitations though, as balconies, windows and doors will look disturbed when seen from oblique views or close distance. This comes from the fact, that rectangular geometries can not be substituted by 2D or 2.5D maps. A geometric refinement of the building façades is therefore necessary for an increased visual appearance. As it will be demonstrated in the following sections, a realistic refinement of window objects based on cell decomposition is well suited for this task.

Pre-processing

In principle, window silhouettes can be detected from terrestrial images [7]. We, however, use a densely sampled point cloud from terrestrial laser scanning as it contains a considerable amount of geometric detail. Such data sets are generally collected from multiple viewpoints in order to allow for a complete coverage of the scene and to avoid any occlusions due to other objects. It is therefore required that a co-registration and geo-coding of the different scans is done in a pre-processing step. For this purpose, control point information is traditionally used from specially designed scan targets. Alternatively, an approximate direct geo-referencing can be combined with an automatic alignment to existing 3D building models [8]. With this information, the point clouds can be transformed into a common reference system and the relevant point measurements extracted for each façade by a simple buffer operation.

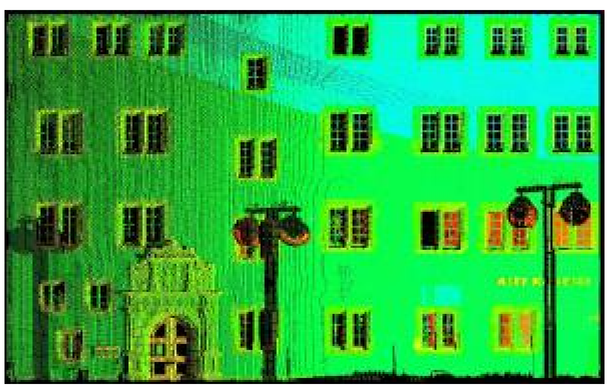

Fig. 2. 3D point cloud used for the geometric reconstruction of building façade.

For instance, the façade points of our example data set were first selected by a buffer operation and then transformed to a local coordinate system. The reference plane was determined for this purpose from the 3D points by a robust estimation process. Due to this mapping of the points, parts of the processing can be simplified by the use of 2D and 2.5D algorithms. Figure 2 shows the transformed LIDAR points that were originally measured with a HDS 3000 scanner at an approximate point spacing of about 4cm.

Cell Generation

The idea of our reconstruction algorithm is to first partition a 3D object with a flat front face into 3D cells. This can either be a coarse building model or some block-like object of the same size as the façade. We then determine which cells are in the window areas and discard them, carving out the window geometry in the process. The remaining cells are for now considered to form a homogeneous façade and are therefore glued together to form the refined 3D façade model. The difficulty is finding planar delimiters from the LIDAR points that generate a good working set of cells. Because our focus is on the geometry of the windows, we need to identify the points that were measured at the window borders. We find those points by a segmentation process.

Point cloud segmentation

As can be seen in figure 2 fewer 3D points are usually measured on the façade at window areas. This is due to specular reflections of the LIDAR pulses on the glass or points that refer to the inner part of the building and were therefore cut off in the pre-processing stage. If we only consider points that lie on or in front of the estimated façade plane, then the windows are areas with no point measurements. Thus, our point cloud segmentation algorithm detects edges by these no data areas. In principle, such no data areas can also be the result of occlusions. However, if the façade was measured from different viewpoints, these occlusions can in most cases be avoided. So only a reduction of the point density can be observed in these areas.

The segmentation differentiates four types of window borders: two horizontal types for the top and bottom, and two vertical types for the left and right window border. As an example, the edge points of the left border of a window are then detected if no neighbor measurements to their right side can be found in a pre-defined search radius. This is necessary as no edge points would be identified otherwise. We used a search radius a little higher than the scan point distance on the façade. As it can be seen in figure 3 a lot of points can be correctly identified this way, although the algorithm often fails to find points at window corners. This is not a real problem, as long as there are enough points to determine the horizontal and vertical boundaries. These are depicted in figure 4 as horizontal and vertical lines, which can be estimated from the non-isolated edge points.

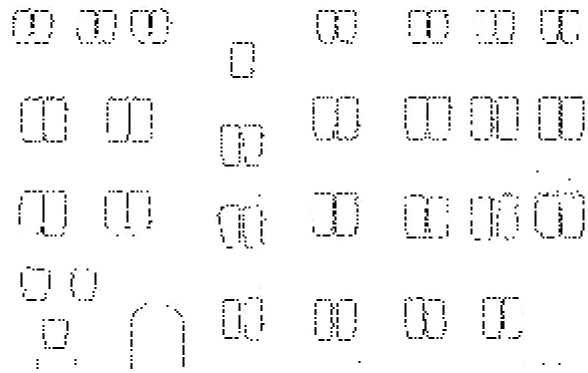

Fig. 3. Detected edge points at horizontal and vertical window structures.

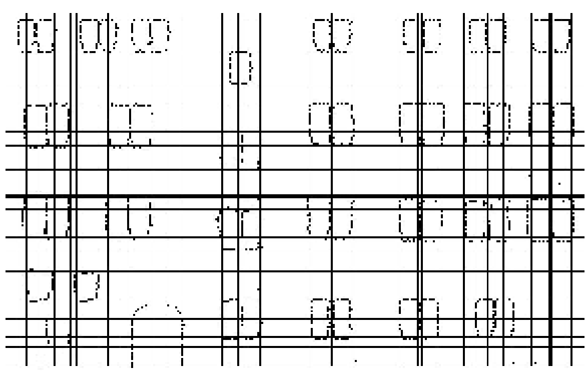

Fig. 4. Detected horizontal and vertical window lines.

Spatial-Partitioning

Each detected boundary line defines a partition plane that is perpendicular to the building façade. They are then used to intersect a cuboid that is aligned and of the size of the façade. Its depth is two times the depth of the windows, which is available from the LIDAR measurements at the cross bars. This is detected by searching for a plane parallel to the façade by shifting it in the planes normal direction. The result of the partitioning of the cuboid by the planes is a set of small 3D cells.

Classification of 3D cells

According to the general outline of our algorithm, all the generated 3D cells have to be classified into building and non-building cells. For this purpose, a binary 'point-availability-map' is generated.

Within this image, which is depicted in figure 5, black pixels are grid elements where LIDAR points are available. In contrast, white pixels define raster elements with no 3D point measurements. Of course, the already extracted edge points in figure 3 and the resulting structures in figure 4 are more accurate than this rasterized image. However, this limited accuracy is acceptable since the binary image is only used for classification of the 3D cells as they are already created from the detected horizontal and vertical window lines. This is implemented by computing the ratio of façade to non-façade pixels for each generated 3D cell.

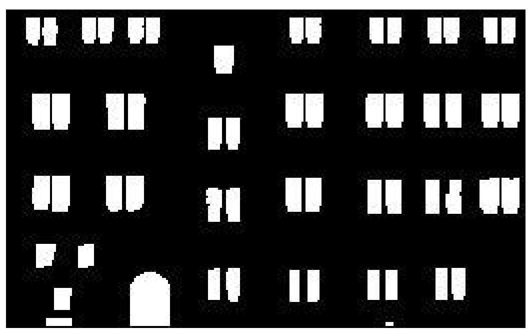

Fig. 5. Binary point-availability-map.

As a consequence of the relative coarse rasterization and the limited accuracy of the edge detection, the 3D cells usually do not comprise of façade pixels or window pixels, exclusively. Within the classification, 3D cells including more than 70% façade pixels are defined as façade solids, whereas 3D cells with less than 10% façade pixels are assumed to be window cells. These segments are depicted in figure 6 as grey and white cells, respectively.

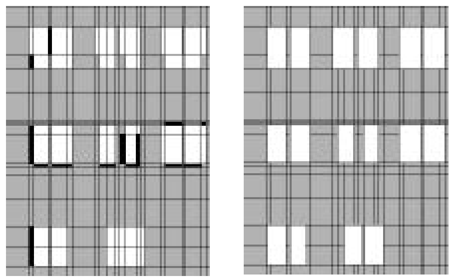

Fig. 6. Classification of 3D cells before (left) and after enhancement (right).

Classification Enhancements

While most of the 3D cells can be classified reliably, the result is uncertain especially at window borders or in areas with little point coverage. Such cells with a relative coverage between 10% and 70% are represented by the black segments in the left image of figure 6. For the final classification of these cells depicted in the right image of figure 6, neighborhood relationships as well as constraints concerning the simplicity of the resulting window objects are used. As an example, elements between two window cells are assumed to belong to the façade, so two small windows are reconstructed instead of one large window. This is justified by the fact that façade points have actually been measured in this area. Additionally, the alignment as well as the size of proximate windows is ensured. For this purpose the classification of uncertain cells is defined depending on their neighbors in horizontal and vertical direction. Within this process it is also guaranteed that the merge of window cells will result in convex window objects.

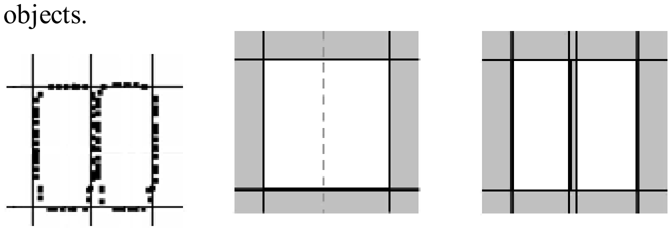

Fig. 7. Integration of additional façade cells.

As it is depicted in figure 7, additional façade cells can be integrated easily if necessary. Figure 7 shows the LIDAR measurement for two closely neighbored windows. Since in this situation only one vertical line was detected, a single window is reconstructed figure 7b. To overcome this problem, a window object is separated into two smaller cells by an additional façade cell. This configuration is kept, if it can be verified as a valid assumption. This occurs if façade points were actually measured at this position figure 7c.

Results and Conclusion

The final result of the building façade reconstruction from terrestrial LIDAR is depicted in figure 8. For this example, window areas were cut out from a coarse model. While the windows are represented by polyhedral cells, also curved primitives can be integrated in the reconstruction process. This is demonstrated exemplarily by the round-headed door of the building.

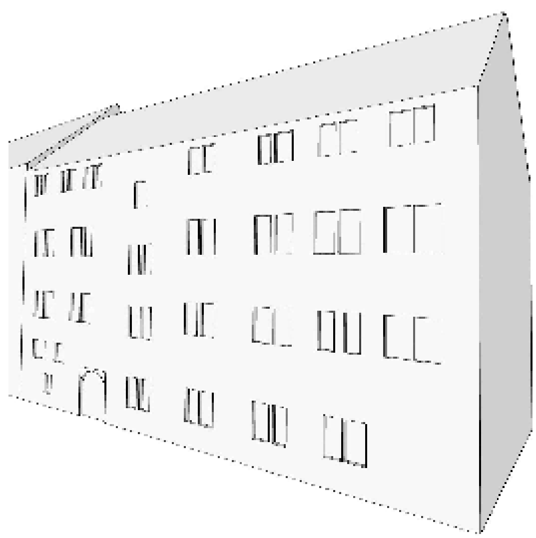

Fig. 8. Refined façade of a 3D building model.

Within the paper, an approach for façade reconstruction based on cell decomposition was presented. The use of cell decomposition proved to be very flexible to add details to an existing building model. While in our approach windows are represented by indentations, details can also be added as protrusions to the façade. Another option is to efficiently subtract rooms from an existing 3D model if measurements in the interior of the building are available.

Still there is enough room for further algorithmic improvement. However, in our opinion the concept of generating 3D cells by the mutual intersection of planes already proved to be very promising and has a great potential for processes aiming at the reconstruction of building models at different scales.

Acknowledgments

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