Robust Reconstruction of Building Models from Three-Dimensional Line Segments

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Abstract
This paper presents a novel method for semi-automatically constructing building models from photogrammetric 3D line segments of buildings, i.e., their roof edges. The method, which we call “Split-Merge-Shape” (SMS), can treat both complete line segments as well as incomplete line segments due to image occlusions. The proposed method is comprised of five major parts: (1) the creation of the Region of Interest (ROI) and preprocessing, (2) splitting the model by using the 3D line segments to construct a combination of roof primitives, (3) merging connected roof primitives to complete the boundary of each building, (4) shaping each building rooftop by connected coplanar analysis and coplanar fitting, and (5) quality assurance. The experimental results indicate that the proposed method can soundly rebuild the topology from the 3D line segments and reconstruct building models with up to a 98 percent success rate. The proposed SMS method has been proved reliable and effective, with a high degree of automation, even when groups of connected buildings or complex types of buildings are processed.

Introduction
Progress in computer technology in the establishment, management, and application of city planning has allowed a move toward the combining of 3D building models with 3D geographic information systems (GIS). Digital 3D building models are useful in true orthophoto generation (Amhar et al., 1998; Rau et al., 2002); map revision; urban planning; change detection; flight, noise, and air pollution simulations; microclimate studies; and the simulation of electromagnetic wave propagation for telecommunications, etc. The generation of reliable and accurate 3D building models thus becomes important.

Related Work
There are three procedures necessary for the generation of 3D building models from aerial photo stereo-pairs, namely, (1) image acquisition and aerial triangulation, (2) feature extraction and stereo-model measurement, and (3) topology reconstruction for building modeling. This paper will focus on the issue of constructing 3D building models based on a semiautomatic approach. In general, there are three approaches for the creation of 3D building models, namely, a manual operation, an automatic approach (Weidner, 1997; Haala and Brenner, 1998; Fischer et al., 1998; Henricsson, 1998; Kim and Muller, 1998; Brenner, 2000; Baillard and Zisserman, 2000), and a semiautomatic approach (Gülch et al., 1999; Grün and Wang, 2001).

In manual operations, 3D building models are measured manually on an analytical stereoplotter or with a digital photogrammetric workstation (DPW). However, the whole process is time-consuming and labor intensive. The operator is responsible for the measurement of roof corners and the structuring of 3D building models. When image occlusions occur, the operator has to estimate the location of hidden corners from the conjugate images. This procedure is tedious and inefficient and has a limited accuracy, especially for connected buildings in densely built-up areas.

Weidner (1997), Haala and Brenner (1998), and Brenner (2000) proposed the use of digital surface models (DSMs) to reconstruct 3D building models. The DSM data can be generated automatically using stereo-pairs, or can be obtained from airborne laser scanning (Lohr, 1996). The problem is that precise building boundaries cannot be well defined due to the segmentation of DSMs. Therefore, other complementary data, such as ground plans of the building outlines, are necessary to assure the reconstruction. This limits the practicability of the approach.

In order to increase efficiency, Fischer et al. (1998) and Henricsson (1998) proposed the use of multi-view aerial images for automatic 3D building model generation. Their first step was to extract features from a 2D image. Some basic 2D image features were used directly for object modeling. Such things as corners or roof patches were further modeled. A building hypothesis was then created and verified by mutual interactions between 2D and 3D processes. However, successful feature extraction relied on good image quality and visible image features. The generation of a building hypothesis could fail in densely built-up areas where building occlusions or shadow effects occur.

Gülch et al. (1999) proposed the use of monocular images and building-based measurements for 3D building model creation, based on a semiautomatic approach. In their system, the operator’s task is to fit a wire-frame model of the selected building type to the building outlines using monoscopic viewing. The operator has to adjust the wire-frame model to fit the corresponding image features by using three possible strategies. These strategies are (1) a purely manual adaption, (2) a guided adaption, or (3) an automated adaption. A complex building could be decomposed into some basic building primitives and structured by a Constructive Solid Geometry (CSG)(Hoffmann, 1989). The operator is also responsible for handling the CSG structures. Although the approach is innovative, the operator has too much responsibility, necessitating a qualified operator. The approach is efficient for isolated and repetitive buildings with a regular structure. However, it encounters some limitations for complex buildings with a polygonal ground plan, especially for polyhedral types of buildings (Gülch and Müller, 2001).
Grun and Wang (2001) proposed a semiautomatic topology generator for 3D building modeling, i.e., the CC-Modeller system, based on manually measured 3D point clouds. These 3D point clouds delineate the roof corners, including the hidden ones, which must be measured or inferred. Although the system is operational, some limitations are still present. They are (1) the measurement of hidden corners caused by building occlusions is necessary to assure the completeness of a roof unit, (2) the structuring may fail if the processed roof unit or object is not in the predefined model database, and (3) the digitizing sequence of boundary points is restricted to be point-wise, which will increase the operator’s workload in decision making when complex and connected buildings are processed.

Objectives and Characteristics
We propose here a semiautomatic approach for 3D building model generation from complete or partially occluded 3D line segments, i.e., the roof edges. From the application point of view, the proposed SMS method is based on the following considerations:

- The whole scheme is semiautomatic; three-dimensional line segments are subject to manual measurement in photogrammetric stereo-pairs, but the building modeling procedure is automated;
- There is no need to establish a building model database, which means that the shapes of the buildings are not limited to any predefined shapes;
- The line-segment digitizing sequence does not need to be specified, which means that the topological relationship between line segments can be built automatically instead of manually;
- Only the visible parts of roof edges need be measured. Both complete segments as well as incomplete segments due to occlusions can be treated; and
- In order to avoid building connection problems, groups of connected buildings can and should be processed simultaneously.

The Split-Merge-Shape Method
General Idea
In the real world, it is difficult to describe all types of buildings using a single comprehensive building model database. In our approach, a building model may be decomposed into several roof primitives. A roof primitive may be part of or a complete building. Each roof primitive has a planar rooftop (e.g., a horizontal plane or an oblique plane) with a vertical wall and a polygonal boundary. One roof primitive, or a combination of roof primitives, can be assembled to form a polyhedral building model. For example, the perspective view of a four-ridge building is shown in Figure 1a. From its ground projection, i.e., Figure 1b, one can observe that the building’s rooftop can be decomposed into four triangular facets. The outline of each triangular facet can be projected as a triangle on the ground. The three roof edges of each triangular facet can be used to construct an oblique rooftop.

The basic idea behind the proposed Split-Merge-Shape (SMS) method comes from the nature of “rain” and the resultant “dripping eaves.” Using a stereo-pair for ground feature delineation, only visible objects can be directly measured. For building boundary delineation, roof corners that have been occluded by higher nearby roofs cannot be measured. These visible boundaries represent the “dripping eaves.” By imaging water falling from the “dripping eaves” of the rooftop, we can produce a polyhedron. The nature of water falling from “dripping eaves” leads to our idea of “splitting.” The nature of rainwater flowing over the roof is analogous to the “shaping” process.

Figure 2 shows the flowchart for the generation of 3D building models using the proposed SMS method. The dashed rectangles depict manual operations. In addition to the manual stereo measurement of the 3D line segments, the core of the SMS method (i.e., the gray boxes in Figure 2) includes the following five parts: (1) the creation of ROI and preprocessing, (2) splitting, (3) merging, (4) shaping, and (5) quality assurance, provided that visible 3D line segments are available. Except for the creation of ROI and the quality assurance, the modeling procedures are fully automatic. In the following sections, the example

![Figure 1. Illustration of a four-ridge building. (a) Perspective view. (b) Ground projection.](image)

![Figure 2. Flowchart of the proposed method.](image)
shown in Figure 3 is used to illustrate the sequence and the intermediate results for each step.

**Stereo Measurements of 3D Line Segments**

In our method, the 3D line segments are manually measured from an aerial stereo-pair. The building outline segment measuring sequence is order-free. Because two consecutive point measurements construct one 3D line segment, for fully visible roof edges the number of "measurements" is equivalent to the corner measurement method, as proposed by Gruen and Wang (2001). However, for partially occluded roof edges, the delineation can be performed using the visible part near the hidden corner. The estimation of the exact location of a hidden corner is thus not necessary. The effort of measurement is thus less than that for the corner measurement method. In addition, the digitizing of the visible part of roof edges that are directly observable in a photogrammetric stereo-model can simplify this task for the operator, which leads to improvements in production efficiency.

**Initialization**

The first step to realize the whole idea is to create an ROI, which is also the first roof primitive with a known topology. The ROI is simply built in such a way that the operator need only specify the region of interest with a polygon that covers a set of 3D line segments. Figures 3a and 3b show a sample area from the original left and right images of a stereo-pair. The white lines denote the both-visible parts of the roof edges manually measured in the stereo-pair. Figure 3c illustrates the measured 3D line segments that are covered by a manually specified rectangle, i.e., the ROI. Be aware that the ROI need not be limited to a rectangle. It can be a polygon of any shape. The ROI together with the selected 3D line segments is shown in Figure 3d.
Due to the manual stereo-measurement errors, some alternative situations should be considered. These situations include (1) two collinear lines are misaligned, (2) rectangular buildings are skewed, (3) two adjacent line segments intersect due to overshooting, and (4) dangle due to image occlusion in complex and connected building blocks may cause modeling failure, etc. In order to obtain a stable solution, these types of problems should be solved in advance.

- **Collinear Processing**
  Collinear processing is used to adjust the line parameters using a pipeline concept. As shown in Figure 4a, if line A and line B are two collinear-like lines, which can be enclosed by a pipeline with a given pipe width (W), then those two lines’ parameters can be replaced by the line parameters of the pipeline’s central line, i.e., line C. The coordinates of each line’s terminals can then be changed accordingly, as shown in Figure 4b. The pipe width is related to the accuracy of the manual measurements and the spatial resolution of the stereo-pair. Generally, “W” is selected at the 2σ level of manual measurement.

- **Orthogonal Processing**
  Considering random errors in the manual stereo-measurements, a rectangular building model may become skewed. One can rectify such building outlines by orthogonal processing. Two perpendicular principal axes are estimated for all line segments, on a 2D horizontal plane, by means of an auto-clustering technique. The auto-clustering technique used is similar to the K-Means clustering algorithm in the field of pattern recognition for automatic feature classification (Duda and Hart, 1973; Schwengerdt, 1997). However, the number of “K” clusters is set as “two” to force the processed line segments to be orthogonal. In the clustering, we choose the longest line’s orientation and its corresponding orthogonal direction as the two initial principal axes. The weights are assigned according to the length of each line segment, because longer lines will yield less error for building orientation. Iterative clustering is performed until convergence occurs.

- **Dangle Removal**
  A dangle refers to a suspended line terminal that is not connected to any line segments. Considering random errors in manual stereo-measurements, two line segments may intersect with overshooting and introduce dangles. Those dangles are considered as a kind of line segment and will result in illegal building outlines. Therefore, we must remove them by changing the coordinates of these lines’ terminals to the intersecting ones.

- **Dangle Snapping**
  Due to building occlusions, a roof edge is occluded and a dangle appears, which will cause the building’s outlines to be incomplete. This is especially obvious when groups of connected or complex buildings are processed. The dangle snapping process extends such a roof-edge until it reaches a wall, and encloses the building outline on the 2D horizontal plane.

Figure 5 illustrates the effect of preprocessing. As shown in Figure 5a, a set of measured building outlines delineating a rectangular gable roof is projected onto the horizontal ground plane. The results of collinear processing are shown in Figure 5b. The effects of orthogonal processing are shown in Figure 5c. It is observed that two dangles hang out from the building, as indicated in the dashed-circles areas. After applying dangle removal processing, the results are shown in Figure 5d, in which the roof edges are still fragmented and the dangles appear. Figure 5e shows the results after performing the dangle snapping process.

### Split
To reconstruct 3D building models from 3D line segments, the key is to build up the topology between adjacent line segments. The SPLIT and MERGE processes will sequentially reconstruct the topology between two adjacent line segments and then reform the areas as enclosed regions. The SPLIT process is also able to cope with building occlusion problems. This process works on a 2D horizontal plane, which means that only the planimetric coordinates of each line segment are treated. By choosing one line segment as a reference, if any roof primitives contain this reference line segment, we SPLIT them into two. At the beginning, the created ROI is treated as the first roof primitive for splitting. For successive line segments, a combination of possible roof primitives is constructed. In splitting, the occluded line is extended to an end wall. This action is similar to the manual inference of hidden corners. Figure 3e shows processed line segments on the 2D horizontal plane, in which the designed preprocessing steps have been applied. One can compare the differences in the dashed-circle areas between Figures 3c and 3e, which reveal some incomplete line segments that have been automatically extended and connected. The total number of 3D line segments is 58. Figures 3f, 3g, and 3h depict the splitting results after applying one, 18, and all 58 line segments, respectively. Finally, the total number of possible roof primitives after splitting is 107.

### Merge
The MERGE process is the second step for rebuilding the topology between adjacent line segments. This merging procedure is also worked on a 2D horizontal plane. Because the ROI is only a virtual shell, to enclose all processed line segments, any roof primitives connected to the ROI boundaries are removed first. Then, every two connected roof primitives are analyzed successively. If any boundary shared between them does not correspond to any 3D line segments, these two roof primitives will be merged into one. Finally, the rationality of each roof primitive is checked. That is, if one boundary of a roof primitive does not correspond to any 3D line segment, such a roof primitive
will be removed. This situation often occurs near the boundary of the ROI, where there is no connected roof primitive for merging analysis.

Please note that the “MERGE” process is also performed on the 2D horizontal plane. The height of each roof edge is arbitrary so far. Figures 3i and 3j illustrate the results after the merging process in 2D and 3D views, respectively. One can find out that the outline of each roof primitive on the 2D horizontal plane is a closed region, but the height for each roof edge is arbitrary. Compared to the results in Figure 3h, the number of roof primitives has been reduced from 107 to 19.

In the Splitting phase, the process sequence is free from constraints. The result will be different when a different sequence of line segments is employed. However, after merging, the reconstructed topology will be identical, except for donut-type buildings. One unique feature of the proposed SMS method is that a donut-type building can be identified, i.e., a building that has a hole or an individual roof primitive inside it. Such a structure is separated as two roof primitives at the end. By taking a close look at the solid-line circled areas in Figures 3c and 3i, one can see that there is one more virtual edge between the outer boundary and the other two roof primitives inside it. This virtual edge is constructed automatically in the splitting and merging process, because the rooftops in the inner and the outer parts are not coplanar. The location of this virtual edge may be different after merging if a different splitting sequence is applied. However, because this edge is only used to separate the inner roof primitive out from the outer roof primitive, its location does not affect the geometrical description of the building model.

Shape

The Shape process is used to infer the rooftop’s height and shape, such as whether it is flat or oblique, from the original 3D line segments. Considering the building occlusion problem, the shaping is processed iteratively. At the first iteration, the fully observable roofs are inferred and their shapes are fixed. During the remaining iterations, the shape of a partially occluded rooftop may be inferred from the surrounding fixed roofs and by its own roof edges. Iteration stops once the rooftop of all roof primitives are fixed.

The first step in shaping is to assign a possible height for every roof edge of a building model from its corresponding 3D line segment. Every roof edge is analyzed and defined as to whether it is a shared edge or an independent edge. An independent edge means that the boundary of the roof primitive is not connected to any other roof primitive at the planimetric location. A shared edge means that two roof primitives are connected by the roof edge at the same planimetric location. Figure 3k illustrates the number of independent edges for each roof patch.

The second step is to infer the shape of each roof primitive according to the available height information. At the first iteration, the fully observable rooftop is inferred and fixed by analyzing whether all its boundaries in the three-dimensional object space are connected or not. In the following iterations, the partially occluded roofs are inferred by analyzing the number of independent edges and their connected or coplanar characteristics:

- If only one independent edge is found, it is necessary to check whether the surrounding rooftops are fixed or not. If they are all fixed and higher than the processing roof primitive, then the shape of such a rooftop can be determined by the independent edge.
- If more than two independent edges exist, and they are sufficient to fit into a planar face, a least-squares coplanar fitting is applied.
- Otherwise, the system will provide the most likely solution by the connected-coplanar analysis. Two connected line segments are always coplanar because their line terminals are connected in 3D space. It is also noticed that two non-connected independent edges may also be coplanar. Therefore, the proposed connected-coplanar analysis is to find a possible planar rooftop using two connected line segments or any two non-connected but coplanar ones.

Quality Assurance

Due to the diversity of building types, manual stereo-measurement errors, and human mistakes, one may encounter topology errors and shaping errors when using the proposed method. Human intervention is required to assure the quality of the modeling.

- If the boundary of the generated building model does not coincide with the original measured 3D line segment on the 2D horizontal plane, it will result in topology errors. If such errors are introduced by human mistakes in the digitizing phase, the operator may need to correct these mistakes manually. If they happen due to stereo-measurement errors, the operator may utilize the preprocessing functions to automatically adjust the original 3D line segments data, and then redo the entire automatic modeling task.
- Because any two connected line segments can define a single planar rooftop, the solution is not unique when the delineation of roof edges is not coplanar. It may introduce shaping errors. An interactive procedure lets the operator easily select the best-fitting rooftop out of all possible rooftops provided by the connected-coplanar analysis. For example, Figure 6a shows a group of selected line segments on the 2D horizontal plane. Figure 6b shows the correct building models in a 3D view. Roof patch A, as indicated with dark thick outlines, delineates roof edges that are not coplanar. Figures 6c, 6d, 6e, and 6f illustrate the four possible solutions provided by the connected-coplanar analysis. An operator can now select the best choice, i.e., Figure 6f.
- The inner roof primitive of a donut-type building still exists after applying the SMS method for building modeling. If it is a hole inside a building, it is difficult to automatically remove it.
such a roof primitive. Human intervention is needed to finalize the procedure.

Case Study
In this section, the robustness, efficiency, and accuracy are all evaluated. In order to investigate the robustness in detail, two types of building groups are examined. The first type is a complex donut-type building, while the second type is a group of connected buildings.

Test Area
One data set of 3D line segments was digitized manually using a DPW. The scale of the original aerial stereo-pair was 1:5,000 with a 60 percent overlap. The focal length of the camera was 30.511 cm. Digital images were digitized with a scanning resolution of 25 μm. The produced images had a nominal ground sampling distance (GSD) of 12.5 cm.

The content of the test area can be abstractly categorized into three parts. Part (I) is a university campus, in which the buildings are large and separated with complex boundaries. Part (II) includes a high-density area with groups of connected and rectangular buildings. Part (III) covers a high-density area with groups of connected, complex rooftops and less-orthogonal buildings. Figure 7a depicts the above three areas on the original aerial photo, on which the manually measured 3D line segments are superimposed. The number of measured roof edges is 6,363. Figure 7b shows the generated 3D building models for this data set.

Robustness Evaluation
The number of roof primitives created using the SMS method was 1,809. The splitting and merging process was totally successful after correction for blunder measurements. However, 38 roof primitives failed at the shaping stage, giving a success rate of 98 percent. The 2 percent failure rate was recovered in the quality assurance phase. The failures occurred mostly in Part (III), where the buildings are connected with a less-orthogonal structure and the rooftops are more complex. An example of this situation has been described previously, and is shown in Figure 6. The performance was mostly satisfactory for Part (I) and Part (II), where the buildings were rectangular in structure, although connected, or with complex boundaries.

To investigate the robustness in greater detail, two cases are now selected and described as follows. Figure 8a shows the original aerial photo, with a ground coverage of about 60 m across and 65 m long, which contains a complex building with a combination of circular and rectangular structures. For the circular boundary, a series of consecutive line segments are measured. This example demonstrates the robustness in dealing with the first type of buildings. The building is a composite of hip, gable, and flat roofs, and also has donut components, with two enclosed courtyards. Figure 8b demonstrates the reconstructed building models in a 3D view. The soundness of the proposed SMS method is quite obvious.

Figure 9a is the original aerial photo, with a ground coverage of about 105 m across and 100 m long, which contains a group of connected buildings. In Figure 9b, the generated building models are shown in 3D. This example treats the second type of building. Again, the SMS method is proven robust for such type of buildings.

Efficiency Estimation
The processing time was based on the use of a personal computer with a Pentium III 1.2-GHz CPU. The processing time depends on the building complexity and the number of line segments in the process. As shown in Figure 10, the processing time versus the number of processed line segments is depicted. In general, for a group of buildings with less than 400 line segments, the processing time for modeling was less than 10 seconds. For example, in detailed examination II, as shown in Figure 9, the number of 3D line segments is 209, which generated 69 roof primitives. The total amount of computer time, including preprocessing and SMS processes, is 1.49 seconds. The response time is so short, that an interactive system is possible.

Accuracy Evaluation
The accuracy of the generated building models primarily depends on the accuracy of the manual measurements. The estimated locations of hidden corners are less accurate than the direct measurement of visible ones. In order to evaluate the modeling error, we utilized manual measurements of visible corners as reference data. Evaluations could be performed accordingly. We measured the section of roof edges that made the
rest of visible roof edges incomplete. Two examples are illustrated in Figure 11 with measured roof edges superimposed. The visible corners are not measured on purpose. The rooftops include both oblique and flat types. The total number of visible corners to be evaluated is 163. After applying the SMS method for building modeling, a mean error of 1.06 cm, 1.22 cm, and 2.73 cm is achieved on the X, Y, and Z axes, respectively. In the meantime, root-mean-square errors (RMSE) of 13.5 cm, 14.5 cm, and 34.9 cm on the X, Y, and Z axes, respectively, are achieved. Because the original stereo pair has a nominal ground sampling distance of 12.5 cm and a base-height ratio of 0.3, the RMSE is close to one pixel at the image scale, which falls into the range of random errors.

Comparison and Summary

Table 1 shows a comparison of the SMS method and two other semiautomatic approaches that are described in the related work. From the comparison, one finds that our method appears advantageous in many aspects. First, our approach can cope with the partial occlusion problem. Second, our method can deal with diverse types of buildings. Finally, our approach can handle a group of connected buildings at the stage of automatic structuring, which is an important asset for modeling densely built-up areas. The proposed SMS method for the automatic structuring of building models using complete and incomplete 3D line segments has proven to be robust and effective. The success rate is high, even in a complex environment. Its advantages and limitations are now listed.

Advantages

The advantages of the SMS method are stated as follows:

- The proposed SMS method is flexible for both generic and complex building types.
- The operator’s task is simplified because the digitizing sequence is free, and tolerant of incomplete roof edge measurements, which reduces the operator’s workload and increases production efficiency and accuracy.
A group of connected buildings can be treated simultaneously, which avoids connection problems between neighboring buildings.

- Building occlusion problems can be handled, which alleviates the difficulty of manual structuring.
- The process is time-efficient and user intervention is minimized. Decision-making is simple, fitting the idea of a semi-automatic approach.

**Limitations**

The limitations of the SMS method are listed as follows:

- A curved surface must be approximated by a set of planar patches, and the curved boundaries are approximated by a set of consecutive lines. Such an approximation increases the operator’s workload and decreases the production efficiency. From the efficiency point of view, it would be more desirable to use a parameterized building model.
- For donut-type buildings, an automatic decision as to whether to remove or to retain them is difficult. Operator decision-making is unavoidable but acceptable, because it is an easy task.
- Human intervention is necessary to assure the correctness and completeness of the modeling.

**Conclusions**

We propose a robust method for reconstructing building models from 3D line segments using a semi-automatic approach with a high degree of reliability and feasibility. The proposed SMS method achieves up to a 98 percent success rate, even when dealing with connected or complex types of buildings. The operator’s workload, as well as the cost, is reduced, even when partially occluded roof edges are used.

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