AN INTERACTIVE SYSTEM FOR PRODUCING POLYHEDRAL AND PRISMATIC BUILDING MODELS USING BUILDING OUTLINE SEGMENTS

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Commission IV, WG IV/1

KEY WORDS: Split-Merge-Shape, Building Modelling, 3-D Line-Segments.

ABSTRACT

This paper presents an interactive system for producing polyhedral and prismatic building models. The core technology, called "Split-Merge-Shape" (SMS) method, reconstruct building models from photogrammetric 3-D line-segments of buildings, i.e. the roof-edges. The method may treat those complete line-segments as well as partial line-segments due to image occlusions. The proposed method comprises four major parts: (1) initialization of a building model and pre-processing of 3-D line-segments, (2) splitting the model by 3-D line-segments to construct a combination of roof-primitives, (3) merging those connected roof-primitives to complete the boundary of each building, and (4) shaping each building rooftop by coplanar fitting. The SPLIT and MERGE processes sequentially reconstruct the topology between any roof edges of the buildings and then reform them as enclosed regions. The SHAPE process uses height information to determine the shapes and heights of the roofs. The results are the polyhedral building models. For most of the 3-D GIS applications the prismatic building models is preferred. So, after modelling the polyhedral building models, prismatic building models can also be created by using an interactive procedure. Experimental results indicate that the proposed method can soundly rebuild the topology among those 3-D line-segments and reconstruct the building models with up to 98% of successful rate. The other 2% of SHAPE failure can be recovered interactively. The proposed system based on the SMS technology can achieve high reliability with high degree of automation even groups of connected buildings and complex buildings are processed. The proposed SMS method can simplify the work of topographic mapping for buildings, and integrated with three-dimensional building modelling thus reducing the operational costs dramatically.

1. INTRODUCTION

1.1 Motivation

Due to progress in computer technology in the establishment, management, and application of city planning, a move toward the combining of 3-D building models with 3-D Geographic Information Systems (GIS) is being made. Traditionally, third dimensional information has been denoted by contour lines or by the number of building stories, which has limited the reliability and feasibility of its applications. Now, with the assistance of computer technology, users can easily analyse spatial data on the fly. Third dimensional ground feature information can be described by geometric models of objects, such as Digital Terrain Models (DTM), Digital Building Models (DBM), or Digital Surface Models (DSM). The primary data for three-dimensional spatial information analysis is the DSM, which denotes all objects on the ground (e.g. trees, buildings, terrain, etc.). The most important feature in urban modelling is the 3-D building model. It is essential in many applications, such as true-orthophoto generation (Rau & Chen, 2002), map revision, cartographic database compilation, change detection, transportation, urban planning, environmental planning (Lange, 1999), flight simulations, noise and air pollution simulations, microclimate studies, wireless networks telecommunication planning (Siebe & Buning, 1997; Leberl, et al., 1999), virtual tourism information querying (Volz & Klinec, 1999), etc. An effective solution for the generation of reliable and accurate building models is thus more urgent than ever.

1.2 Related Works

Since 3-D mapping is increasing in importance, some Digital Photogrammetric Workstations (DPWs) have developed new functions that will create DBMs directly, and integrate them into topographic mapping. However, image occlusion is still the

biggest problem in the manual delineation process. The operator is responsible for the measurement of roof corners and the structuring of building models. Whenever image occlusions occur, the operator has to estimate the hidden corners from conjugate images. The whole process is time-consuming and labour intensive, as well as tedious, inefficient and produces with a limited accuracy, especially for connected buildings in densely built-up areas.

Except for the ***manual operations*** necessary for building modelling in some DPWs, most of the related work can be categorized into two approaches, according to the degree of human intervention required for topological reconstruction. The two approaches are the ***automatic approach*** (Baillard. and Zisserman, 2000; Fischer, et al., 1998; Henricsson, 1998) and the ***semi-automatic approach*** (Gülch, et al., 1999; Grün & Wang, 1998).

Gülch, et al. (1999) proposed the use of monocular images and building-based measurements for 3-D city model creation. Their approach is based on a ***semi-automatic*** scheme. In manual modelling, the operator's task is to fit a wire-frame building model, which is selected from a predefined model database, to the images, via monoscopic viewing. The operator has to adjust the wire-frame model to fit the corresponding image features. A complex building is decomposed into some basic building types

and constructed using a Constructive Solid Geometry (CSG) tree. The operator is also responsible for handling the CSG tree structures. Although the approach is innovative, the operator takes too heavy a responsibility, necessitating a qualified operator. The approach may be efficient for simple structure and specific type of building, but not for groups of connected buildings in densely built-up areas where occlusions and shadows frequently occur.

Grün & Wang (1998) proposed a topology builder, i.e. the CC-Modeler system, for the generation of building models. The system is based on a *semi-automatic* approach, utilizing manually measured 3-D point clouds. The measurement of 3-D point clouds, denoting all roof corners must be complete, including any hidden ones. The system is a model-based approach, but it can be applied to general objects, such as roads, rivers, parking lots, ships, etc. During data acquisition, 3-D point clouds are manually coded as boundary points and interior points, according to their functionality and structure. Although the system is operational, some of their limitations cannot be ignored. Those limitations are stated as follows. (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 pre-defined model database. (3) The boundary point digitizing sequence must be restricted to being point-wise. (4) Each roof unit or object needs to be processed independently, which leaves connection problems between two buildings to the operator.

2. POLYHEDRAL BUILDING MODELLING

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 planar *roof-primitives*. A roof-primitive may be a part or a complete building. Each roof-primitive is a planar rooftop, (e.g. a horizontal or oblique plane), with its boundary projected onto the ground as a polygon. One roof-primitive, or a combination of roof-primitives, can be reformed as a *polyhedral building model*.

2.1 Initial Building Model

The key for the realization of the whole idea is to create an initial building model, which is the first roof-primitive with a known topology. The initial building model is simply built in such a way that an operator needs only to specify the Area Of Interest (AOI) with a polygon. By the incorporation of a reasonable height, a volumetric representation of the initial building model, which covers all of the 3-D line-segments in a process. Briefly speaking, the creation of initial building model has the following two important meanings: (1) the first building model with a known topology, and (2) the selection of working line-segments.

2.2 Pre-Processing Functions

There are two reasons for pre-processing the manually measured 3-D line-segments. One refers to the adjustment of geometric irregularities due to stereo measurement errors, the other to obtaining a topology error-free solution. Many geometric irregularities due to the errors of manual stereo measurement can happen, such as: (1) two collinear lines are misaligned, (2) rectangular buildings are skewed, (3) two consecutive line-segments intersect and cause overshooting, and

(4) gaps due to image occlusions, especially in a densely built-up area, may cause incorrect modelling. These kinds of situations should be solved before building modelling. Since the roof-edges are measured in the 3-D object space, these pre-processing steps are also performed in the object space.

2.3 Split-Merge-Shape

A novel building modelling method, called "SPLIT-MERGE-SHAPE" Method, was proposed by Rau (2002). A brief discussion of the method is described below.

The SPLIT and MERGE processes can sequentially reconstruct the topology between two consecutive line-segments and then reform the areas as enclosed regions. In splitting, one line-segment is chosen as a reference. If any roof-primitives contain this line-segment, we SPLIT them into two. For successive line-segments, a combination of the possible roof-primitives is constructed. The splitting action is similar to the manual inference of hidden corners. The merging procedure is also worked on the 2-D horizontal plane. Every two connected roof-primitives are analysed successively. If the boundary shared between them does not correspond to any 3-D line-segments, the two roof-primitives will be merged into one. The SHAPE process is worked in 3-D object space. The first step of shaping is to assign a possible height for each roof-edge from its corresponding 3-D line-segment. Every roof-edge is automatically labelled as a *shared edge* or an *independent edge* at first. The height information for an *independent edge* can then be assigned and fixed from its corresponding 3-D line-segment. The second step is to define the shape of a rooftop according to the height of the independent edges. If more than two independent edges exist and are sufficient to fit into a planar face, then least-squares coplanar fitting can be applied. Otherwise, the system will provide the most possible solution by *consecutive-coplanar analysis*, which is used to find a possible planar rooftop using consecutive line-segments or any two non-consecutive but coplanar ones.

2.4 Post-Processing Functions

The proposed SMS system is designed to have some *post-processing functions* for visual inspection and modification. In the visual inspection stage, each generated roof-primitive is examined both on the ground view and 3-D view.

1. The user can *select* the roof-primitive of interest on the ground view. The selected roof-primitive together with the original 3-D line-segments will be shown in the 3-D view.
2. Whenever the selected roof-primitive doest not fit the original line-segments, *reshaping* is necessary. The system will provide all possible solutions by the consecutive-coplanar analysis and show them on the screen one by one. The operator can thus choose the correct one by comparing the original stereo-pair.

3. PRISMATIC BUILDING MODELLING

Complex buildings may be decomposed into many coplanar roof-primitives when a polyhedral model is employed. In general, the attributing of a building is in "house" unit, or belonging to the same "owner". It is practical to relate the roof-primitives that belong to the same owner as one attribute when a complex building is described with a polyhedral model. However, a generalization of this polyhedral models will simplify the above attributing task. As discussed earlier,

prismatic models can describe complex buildings with flat roofs, with polygonal ground plans and with vertical walls. It is a generalized form of the polyhedral model, but the attributes of a complex building can thus be directly assigned. Here, we provide a solution to create prismatic models interactively from the existing polyhedral models. The techniques used are similar to the SMS method. The generation of prismatic model includes the following three steps:

3. Manually select the neighbouring roof-primitives that belong to the same "house". Since the selection of roof-primitives that belong to the same "house" unit needs to be accurate, an operator needs to have a priori information about the house unit. Cadastral maps, for instance, are needed when ownership is considered. This step is performed on the ground view. For example, the operator selects five roof-primitives that belong to the same house unit, i.e. denoted in green in figure 1(a). In the 3-D view, i.e. in figure 1(b), the selected roof-primitives are chosen and also depicted in green.

4. After selection, the operator automatically fuses them into one house unit, using a technique similar to the SMS MERGE step. The major difference is that shared boundaries should be totally removed. In the meantime, the system provides an estimation of the possible height value, i.e. the green one in figure 1(c). The height estimation is designed to find the lowest height for the greatest area. However, this may not meet the topographic mapping protocol, since this estimation may influence the calculation of the number of stories. Therefore, we provide an interactive mechanism for the operator to make the best choice.

5. In the third step, i.e. shape, the operator can then change the height iteratively, using an interactive mechanism similar to the SMS shaping process. The provided height values are estimated automatically from the original five roof-primitives. Notice that roofs are forced to be flat.

Using of the same procedures the other parts can be performed completely, as shown in figures 1(d), 1(e), and 1(f). The previous fused result is depicted in pink. Finally, we can use the 3-D visualization tool to verify the final prismatic models, i.e. figure 1(g). For the purpose of comparisons, the original polyhedral models are illustrated in figure 1(h). The effect of the generalization from a polyhedral model is quite obvious. The provided interactive procedures are easy to use. No complicated designs and no tedious operations are required.

4. CASE STUDY

In theory, the proposed SMS method can cope with partial occlusion problems. Except for the manually measured visible roof-edges from the quadruplet, a digital topographic map of building outlines are also tested to evaluate the robustness, efficiency, and accuracy of the proposed method.

4.1 Line-Segments from Visible Roof-Edges

The test data set was measured manually using a DPW. The content of this data set can be abstractly categorized into three parts. Part (I) is a university campus, i.e. Fu-Zen University, TAIWAN. The buildings are large with complex boundary, and are separated to each other with a distance. Part (II) is a high-density built-up area with groups of connected and rectangular buildings. Part (III) is a high-density built-up area with groups of connected, complex rooftops, and less-orthogonal buildings. Figure 2 depicts the above three areas on one of the original aerial-photos superimposed by manually measured 3-D line-segments. The number of measured roof-edges is 6,363. Figure

3 depicts the reconstructed polyhedral building models for this data set displayed using the 3-D visualization tool.

The number of roof-primitives created using the SMS method was 1,809. The splitting and merging process was totally successful after the correction of blunder measurements. However, 38 roof-primitives failed at the shaping stage, giving a success rate of 98%. The 2% failure rate was totally recovered using the provided *post-processing functions,* without any manually editing of building models. These failures occurred mostly in Part (III), where the buildings were connected with a less-orthogonal structure and the rooftops were complex that the delineation of roof-edges is not coplanar in nature. The performance was totally satisfactory for Part (I) and Part (II), where the buildings were rectangular in structure, although connected, or with complex boundaries. This investigation demonstrated the robustness of the proposed method that diversified types of buildings could be modelled.

In order to investigate the robustness in detail, two types of building group are demonstrated. The first type of buildings, depicted in figure 4(a), contains a complex building with a combination of circular and rectangular boundaries. The building is a hip roof, gable roof, flat roof composite, and also has two donut components with courtyards inside. Under a PC with Pentium III 800Mhz CPU, the process time of modelling for this group of buildings is less than one second. For the circular boundary, a series of consecutive line-segments are measured. The second type of building, shown in figure 4(b), contains a group of connected and mixed rooftop types. The number of 3-D line-segments is 209, which generates 69 roof-primitives at last. The process time for this group of buildings takes only 1.5 seconds. The hidden effects are problematic for manual measuring and building modelling. The SMS method is proven to be robust for the second type of buildings, where image occlusions frequently happen. It is also efficient even for a group of buildings is processed and which is suitable for a semi-automatic approach of building modelling.

The accuracy of the generated building models mostly depends on the accuracy of the manual measurements. The estimated locations of hidden corners were less accurate than the direct measurement of visible ones. In order to evaluate the modelling error, we considered the manual measurements of visible corners as reference data, so evaluations could be performed accordingly. We measured the parts-of-the-roof-edges that makes the totally visible roof-edges incomplete. The total number of visible corners being evaluated is 163. After applying the SMS method for building modelling, it achieves a MEAN error of 1.06 *cm*, 1.22 *cm*, and 2.73 *cm* on the X, Y and Z-axis, respectively. In the mean time, a Root-Mean-Square Error (RMSE) of 13.5 *cm*, 14.5 *cm*, and 34.9 *cm* on the X, Y and Z-axis, respectively, is achieved. Since 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 be one pixel on the image scale, which falls into the range of random errors. It is proven that the proposed SMS method is accurate in modelling.

4.2 Creating Prismatic Models

Here we use the polyhedral building models generated from the previous section to create the prismatic models. Here we present a case study of building models imported to the Arc View 3D Analysis module. A 3-D building stories query procedure is demonstrated. The determination of the number of stories needs information about the *real height* of a building, which is a

subtraction of the *absolute height* from the *terrain*. Therefore, DTM data is a must in the conversion process. The DTM we used is part of a topographic database on Taiwan. We assume the buildings have an average height of 3.3 *m* per story. Thus, the number of stories in a building is determined by dividing the real height by 3.3 *m*. This attribute, together with the prismatic models, can be transformed into the Shapefile format and analysed using the ArcView software, as shown in figure 5. The user can pan or zoom using 3-D roaming. The users can also query the number of stories in a building, e.g. the upper-left window in figure 5. The number of stories in each building is differentiated by colour, e.g. the middle-left window in figure 5.

4.3 Building Outlines from a Digital Topographic Map

In the creation of digital topographic maps, the stereo-measurements are mapped onto the ground plane to produce planimetric maps. This means that the measurements are made in three-dimensional space. Figure 6, for instance, shows a digital topographic map of Kao-Hsiung City, TAIWAN. The map scale is 1:1,000 and it contains a number of detailed ground features such as buildings, roads, trees, fence, and so on. We select the building layer and project it back onto the original aerial photo, as shown in figure 7. Since this is a large-scale urban topographic map, the delineation of building outlines is very detailed. By applying the proposed SMS method we can generate a 3-D city model. The result is illustrated in figure 8 using the 3-D visualization tool. This experiment depicts the following important issues.

1. Conventional stereo-measurement of buildings in the original 3-D line-segments form can be efficiently and directly converted to make a city model, which means that existing urban topographic maps with 3-D building outlines are useful for 3-D city model generation.

2. The protocol for the topographic mapping of buildings may be evolved to only measure the visible part of roof-edges. The manual post-editing of a topographic map on the X-Y plane can be replaced by the proposed SMS method automatically. This may reduce the workload of the operator during post-editing phase. Moreover, geometrically regular buildings can be restored automatically by the pre-processing functions.

3. We provide the possibility of integrating topographic mapping with 3-D city modelling, to make the 3-D mapping more cost-effective.

5. CONCLUSIONS

This paper presents a novel method for geometrical building modelling. The proposed Split-Merge-Shape method that adopts manually measured visible roof-edges for building modelling is innovative. Table 1 compares the SMS system with two other semi-automatic approaches as described in section 1.2. From the comparison, one finds that our method appears advantages in many aspects. The major features of the method are:

1. It can handle a group of buildings simultaneously to avoid possible topology errors in neighbouring buildings.
2. It can cope with partial occlusion problems.
3. It can deal with diverse types of buildings.
4. It is proven to be robust, efficient, and with high accuracy.
5. Due to only visible roof-edges are required and the digitising sequence is free, the operator's workload is reduced as well as the cost of production.
6. The designed SMS system can create polyhedral and prismatic building models in an efficient way. It fulfills the requirements for many applications not only in the field of

photogrammetry, but also in GIS, remote sensing, computer vision, environmental studies, etc.

7. An existing digital topographic map that includes buildings outlines can be directly converted to be a 3-D city model without any additional manual measurement.

8. By means of the SMS technology, the integration of topographic mapping with 3-D building modeling is possible. A cost-effective environment could be established for 3-D mapping.

7. REFERENCES

Baillard, C. and A. Zisserman,(2000). A plane sweep strategy for the 3D reconstruction of buildings from multiple images, *Proc. of International Archives of Photogrammetry and Remote Sensing,* Vol.33, B3, Amsterdam, Netherlands, pp.56-62.

Fischer, A., T. H. Kolbe, F. Lang, Cremers, A. B., Förstner, W., Plümer, L. & Steinhange,V.,(1998). Extracting Buildings from Aerial Images Using Hierarchical Aggregation in 2-D and 3-D, *Computer Vision and Image Understanding*, Vol.72, No.2, Nov. pp.185-203.

Grün, A. and X. Wang,(1998), CC-Modeler: A Topology Generator for 3-D Building Models, International Journal of Photogrammetry and Remote Sensing, Vol.53, pp.286-295.

Gülch, E., H. Muller & T. Labe,(1999). Integration of Automatic Processes Into Semi-Automatic Building Extraction, *Proc. of ISPRS Conference "Automatic Extraction Of GIS Objects From Digital Imagery"*, September 8-10, (INVITED).

Henricsson, O.,(1998). The Role of Color Attributes and Similarity Grouping in 3-D Building Reconstruction, *Computer Vision and Image Understanding*, Vol.72, No.2, pp.163-184.

Lange, E.,(1999). The degree of realism of GIS-based virtual landscapes: implications for spatial planning, *Photogrammetric Week* (Fritsch, D. and Spiller, R., Eds.), Wichmann, Karlsruhe, pp. 367-374.

Leberl, F., W. Walcher, R. Wilson and M. Gruber,(1999). Models of urban areas for line-of-sight analyses, *Proc. of International Archives of Photogrammetry and Remote Sensing*, Vol.32, Part 3-2W5, Munich, Germany, pp.217-226.

Rau, J.Y. and L.C. Chen,(2002), True Orthophoto Generation of Built-Up Areas Using Multi-View Images, *PE & RS*, (Accepted).

Rau, J.Y.(2002), Geometrical Building Modeling and Its Application to the Ortho-Rectification for Aerial Images, Ph.D. Thesis, National Central University, R.O.C.

Siebe, E. and U. Buning,(1997). Application of digital photogrammetric products for cellular radio network planning, *Photogrammetric Week* (Fritsch, D. and Spiller, R., Eds.), Wichmann, Karlsruhe, pp.159-164.

Volz, S. and D. Klinec,(1999). Nexus: the development of a platform for location aware application, *Proc. of the third Turkish-German Joint Geodetic Days*, Vol.2, Istanbul, Turkey, pp. 599-608.
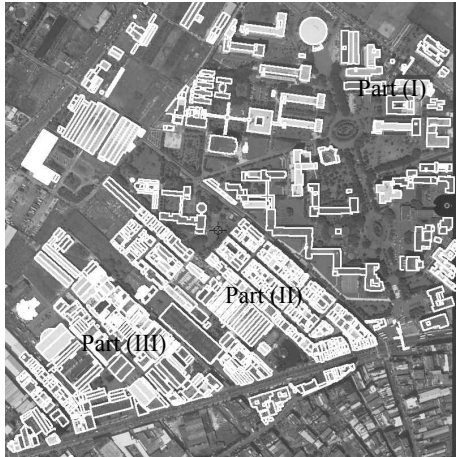
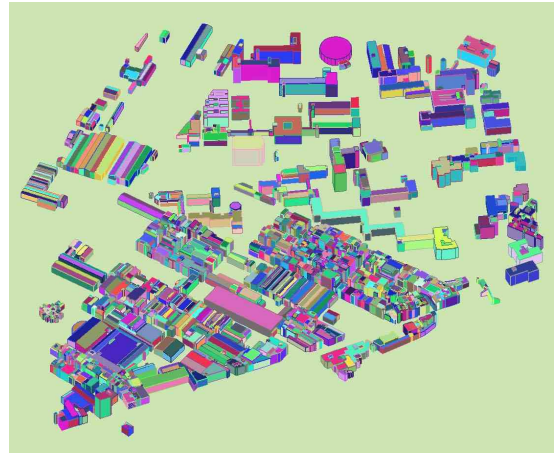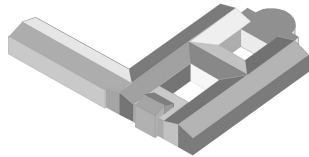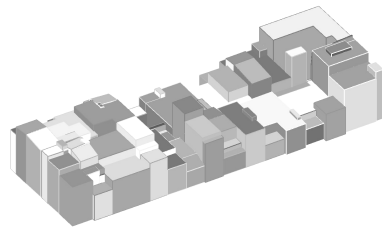Figure 2. Original aerial-photo with delineated roof-edges.

Figure 3. The generated 3-D building models in a 3-D view.

(a)

(b)

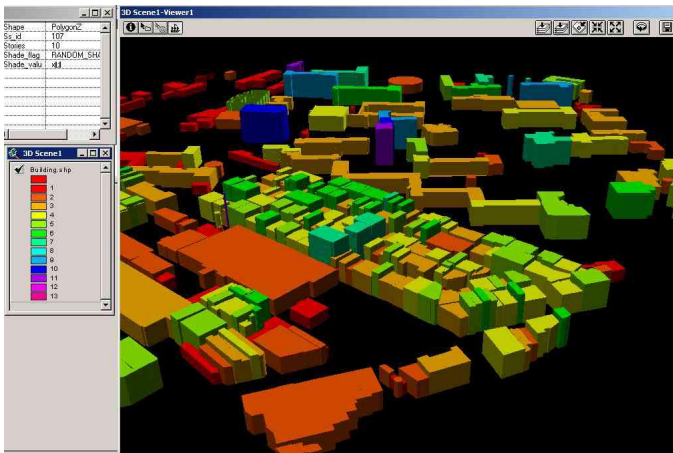Figure 4. Two detail example of generated building models.

Figure 5. An example of 3-D querying in the ArcView environment.

Figure 6. Example of a digital topographic map.

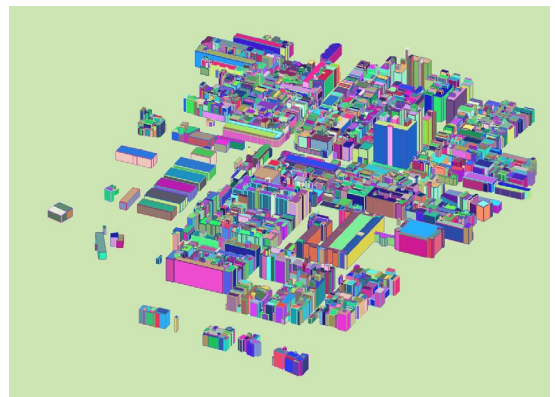Figure 7. A digital topographic map of building outlines superimposed onto the aerial photo.

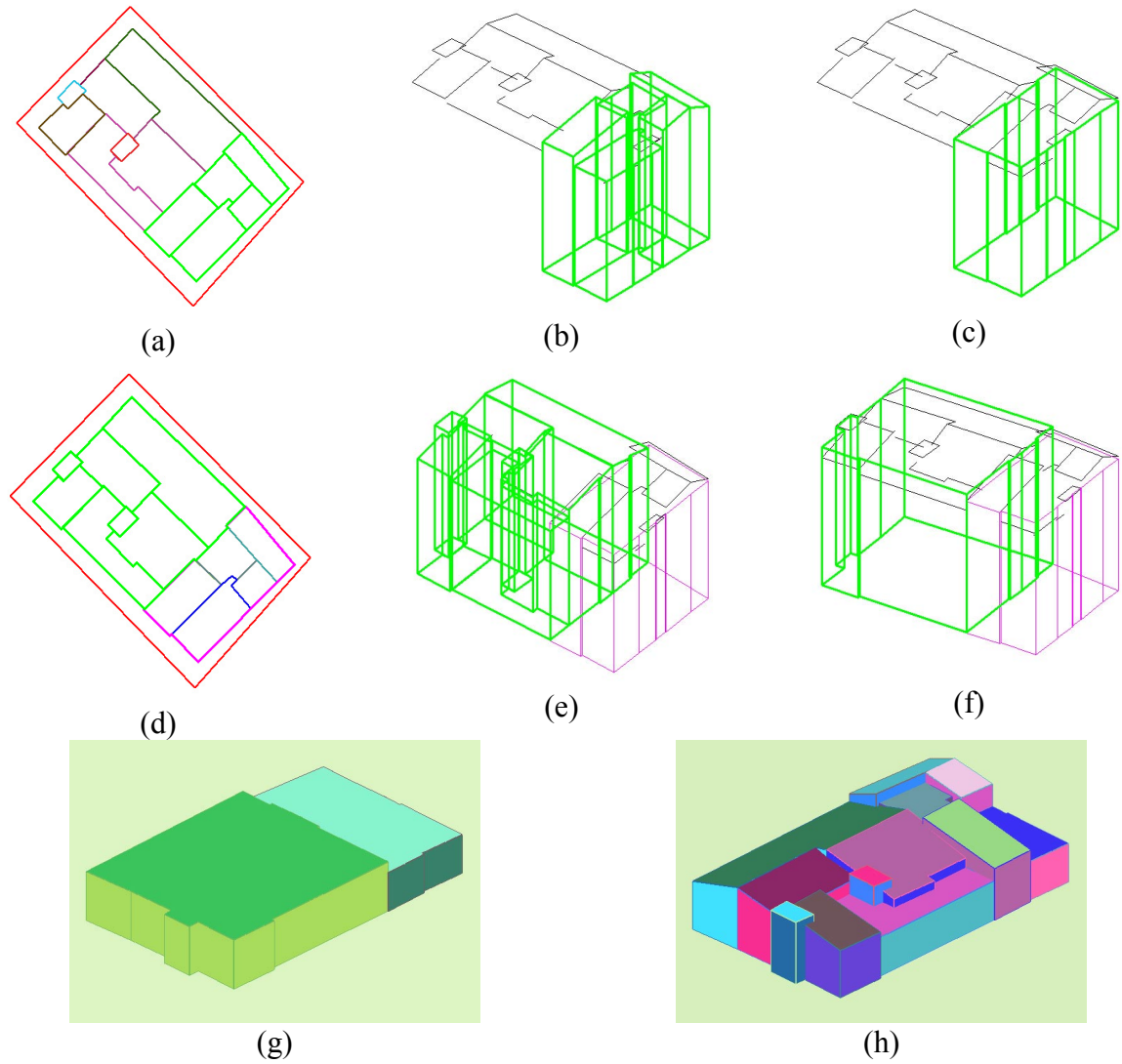Figure 8. 3-D city model generated from a digital topographic map of building outlines.

Figure 1. Procedure for creating prismatic models.

Table 1. Comparisons of the proposed SMS system with two semi-automatic approaches.

	SMS	Grün & Wang (1998)	Gülch, et al. (1999)
Viewing	Stereo	Stereo	Mono In Multiple Images
Measurement	Incomplete 3-D Roof-Edges	Complete 3-D Roof Corners	Building Primitives
Digitizing Sequence	Free	Point-Wise for Boundary Points	Free
Hidden Corners	Automatically Generated	Needs Measurement	Not Measured
Can Handle a Group of Connected Buildings	Yes	No	No
Model-Based	No	Yes	Yes
Automation	Building Model Reconstruction	Object Model Reconstruction	Height Determination Parameter Estimation
Accuracy	Photogrammetry	Photogrammetry	Photogrammetry
Outputs	Polyhedral & Prismatic Models	Polyhedral Objects	CSG Structure of Buildings
Post Processing	Needed	Needed	Needed