

# Model-based Building Reconstruction from Topographic Maps and LiDAR Data

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**KEY WORDS:** Building Reconstruction, CSG Model, Lidar Data, Topographic Map, Virtual City

**ABSTRACT:** A novel approach of *Model-based Building Reconstruction* (MBBR) from topographic maps and LiDAR data called *Floating Models* is proposed in this paper. Floating models are a series of pre-defined primitive models which are floating in the space. Its size is adjustable by shape parameters, while its location and rotation is controlled by pose parameters. A building is reconstructed by adjusting these model parameters so the wire-frame model adequately fits into the building's outlines among the topographic maps, LiDAR data, aerial photos and DEM. This model-based reconstruction provides good constraints to the shape of the model in contrary to the data-based approach. In this paper, the model parameters are re-arranged into two groups: plane and height parameters. The plane parameters are determined by fitting the top or bottom boundary of the model to the topographic maps. The height parameters are decided by fitting the top surface of the model to the lidar data and interpolating the datum point's height from DEM. The proposed reconstructing procedure is semi-automated. First, the operator chooses an appropriate model and approximately fit to the building's outlines on the topographic map. Second, the computer computes the optimal fit between the model and the topographic map based on an *ad hoc* least-squares model fitting algorithm. Third, the computer computes the roof or ridge height from the lidar points within the roof's boundary. Finally, the model parameters and standard deviations are provided, and the wire-frame model is superimposed on all overlapped aerial photos for the operator to check the result. The operator can make any necessary modification by adjusting the corresponding model parameter. We select a small urban area of Taipei City for testing the proposed approach. The fitting result is compared to the traditionally photogrammetric result. Most of the modern buildings can be modeled smoothly, and fitting result achieves the photogrammetric accuracy.

## 1. INTRODUCTION

In response to the development of 3D City Spatial Information Systems for urban planning and management, acquisition of 3D data of city objects has increasingly become an important topic (Braun et al., 1995; Englert and Guelch, 1996; Gruen, 2000; Lang and Foerstner, 1996; Vosselman and Veldhuis, 1999). Conventional photogrammetry concentrates on the accurate 3D coordinate measurement of points. The automated measuring systems set up by image matching algorithms are still based on the point-to-point correspondence. However, higher-order features such as linear, planer or volumetric features contain much more geometric and semantic information than a single point.

The increasing demands of object's 3D models encourage many researches toward using 3D CAD models as a modeling tool to extracting objects from image data (Bhanu et al., 1997; Boehm et al., 2000; Brenner, 2000; Das et al., 1997; Ermes, 2000; Tseng and Wang, 2003; van den Heuvel, 2000). This trend towards integration of photogrammetry and CAD system in the algorithmic aspect creates a new term: "*CAD-based Photogrammetry*". Researches show that

using CAD models does increase the efficiency of photogrammetric modeling by two reasons: (1) the advanced object modeling techniques such as Constructive Solid Geometry (CSG), (2) the incorporation of geometric object constraints.

Inspired by the CAD-based photogrammetry, we proposed a novel measuring tool – *floating model* – for reconstructing building from both 2D and 3D data. The floating model represents a flexible entity floating in the 3D space. It can be a point, a line segment, a surface plane, or a volumetric model. Each model is associated with a set of shape parameters and a set of pose parameters. The pose parameters determine the datum point’s position and the rotation of the model. The shape parameters change the model’s outline and volume. From the traditional photogrammetric point of view, the floating model is an extension of the floating mark. Instead, it is not only floated in the object space, but also deformable to fit the outline of the object. From the model-based building reconstruction’s point of view, floating mark is an exceptional case of floating model without any shape parameter. Three kinds of primitive models – box, gable-roof, and polygonal prism – are designed for building reconstruction in our case study.

Model-based building reconstruction (Ameri, 2000; Brenner, 1999; Sester and Foerstner, 1989; Wang and Tseng, 2004) starts with hypotheses of building model representing a specified target on the scene, and verifies the compatibility between the model and the existing data, such as topographic maps, aerial photos, LiDAR data, and DEM. Approaches to MBBR are mostly implemented in a semi-automatic manner, solving the model-data fitting problem based on some high-level information given by the operator. The spatial data of a building object are determined, when model-data fitting is achieved optimally. Therefore, the key is the algorithm that is able to determine the pose and shape parameters of a floating model such that the edge lines of the wire-frame are optimally coincided with the corresponding edge pixels. To deal with this problem, we proposed a tailored *Least-squares Model-data Fitting* (LSMDF) algorithm as a major component of the building reconstruction framework.

To simplify the fitting problem, the model parameters are rearranged into two groups, plane and height parameters. Hence the model-data fitting procedures are also divided into three steps. First, fit model to topographic maps to derive plane parameters. Second, interpolate datum’s height from DEM and fit model to LiDAR data to derive height parameters. Finally, the wireframe model is projected onto aerial photos for examining. The operator can make further modification of the model according to the photos if necessary. Fig. 1 uses a box model as an example to depict the proposed reconstruction procedures.

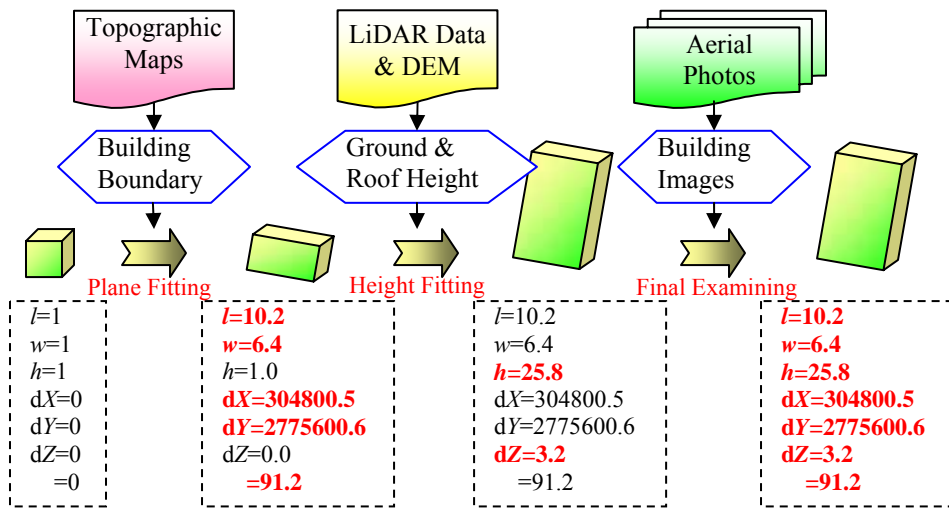


Figure 1. The flowchart of the proposed reconstruction procedures.

## 2. FLOATING MODELS

Traditional photogrammetric mapping systems concentrate on the accurate measurement of points. The floating mark is a simple way to represent the position of a point in the space, and thus, has been served as the only measuring tool on the stereo plotters up to nowadays. However, the floating mark reaches its limits when the conjugate points can not be identified due to the occlusions or interferences from other noises. And with the increasing needs of 3D object models, point-by-point measurement has been become the bottleneck of the production. To deal with the modeling problem, we proposed floating models which complies with the constructive solid geometry. The floating model is basically a primitive CSG model, which determines the intrinsic geometric property of a part of building. That can be categorized into four types: point, linear feature, plane, or volumetric solid. Each type contains various primitive models for the practical needs. For example, the linear feature includes the line segment. The plane includes the rectangle, the circle, the triangle, *etc.* The volumetric solid includes the box, the gable-roof house, *etc.* Despite the variety in their shape, each primitive model commonly has a datum point, and is associated with a set of pose parameters and a set of shape parameters. The datum point and the pose parameter determine the position of the floating model in object space. It is adequate to use 3 translation parameters ( $dX$ ,  $dY$ ,  $dZ$ ) to represent the position and 3 rotation parameters, tilt ( $t$ ) around  $Y$ -axis, swing ( $s$ ) around  $X$ -axis, and azimuth ( $\alpha$ ) around  $Z$ -axis to represent the rotation of a primitive model. Fig. 2 shows four examples from each type of models with the change of the pose parameters.  $X'-Y'-Z'$  coordinate system defines the model space and  $X-Y-Z$  coordinate system defines the object space. The little pink sphere indicates the datum point of the model. The yellow primitive model is in the original position and pose, while the grey model depicts the position and pose after changing pose parameters ( $dX$ ,  $dY$ ,  $dZ$ ,  $t$ ,  $s$ ,  $\alpha$ ). It is very clear that, the model is “floating” in the space by controlling these pose parameters. The volume and shape of the model remain the same while the pose parameters change. The shape parameters describe the shape and size of the primitive model, e.g., a box has three shape parameters: width ( $w$ ), length ( $l$ ), and height ( $h$ ). Changing the values of shape parameters elongates the primitive in the three dimensions, but still keeps its shape as a rectangular box. Various primitive may be associated with different shape parameters, e.g., a gable-roof house primitive has an additional shape parameter – roof’s height ( $rh$ ). Fig. 3 shows three examples from each type of models with the change of shape parameters. The point is an exceptional case that does not have any shape parameters. Fig. 3 points out the other important characteristic of the floating model – the flexible shape with certain constraints. Changing the shape parameters does not affect the position or the pose of the model.

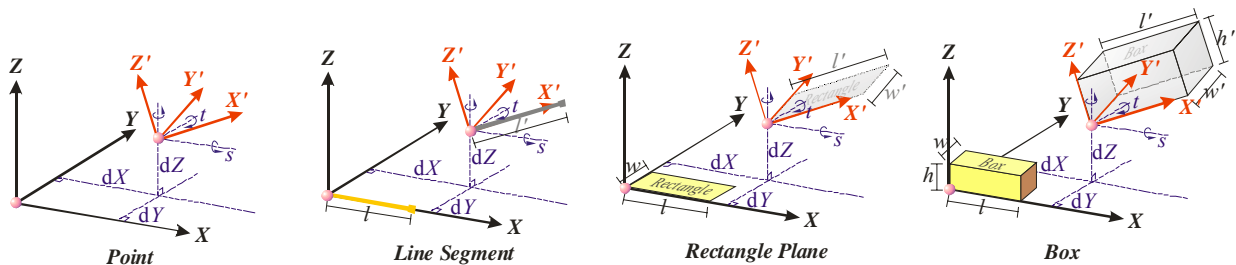


Figure 2. Change the pose of floating models by adjusting pose parameters.

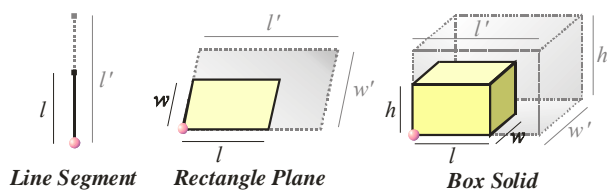


Figure 3. Change the shape of floating models by adjusting shape parameters.

### 3. LEAST-SQUARES MODEL-DATA FITTING

Since the topographic maps are plotted by photogrammetric techniques, its plane accuracy would be better than the LiDAR data. On the contrary, the LiDAR data provides better height accuracy. Therefore, the proposed model-data fitting procedures are separated into two steps: (1) the plane parameters are derived by fitting model's bottom to the topographic map; (2) the height parameters are derived by fitting model's roof to the LiDAR data.

The objective of the plane fitting is the building's boundary on the topographic map. However, the map contains much more elements than building boundaries. A "clean & build" process is necessary to establish the close-and-complete polygons of only buildings. These polygons are the bases of plane fitting. The operator selects an appropriate primitive model and makes the approximately fit according to the polygon to be measured. The corresponding polygon's boundary is then re-sampled as sample points with fixed interval. Each sample point would be treated as an observation in the LSMDF to solve the plane parameters as optimal fit. Fig. 4 depicts the flowchart of the plane fitting.

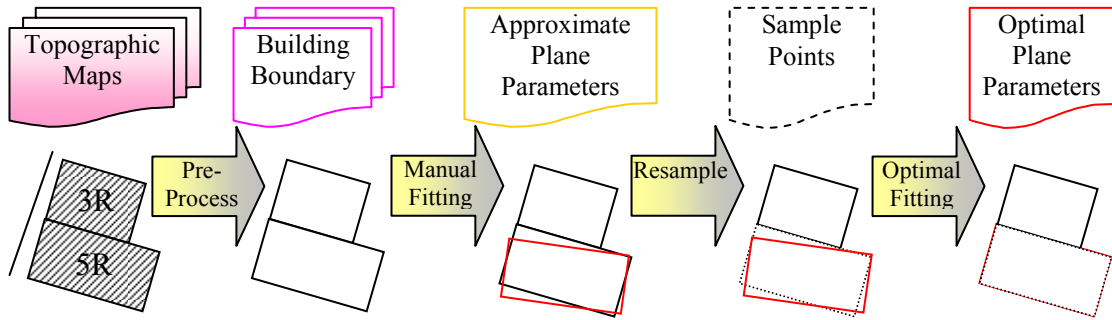


Figure 4. The flowchart of plane fitting.

Since the model has been manually fit, the bottom edges of the wireframe model should be close to the building's boundary on the map. Benefited from the approximate fitting, the LSMDF iteratively pulls the model to the optimal fit instead of blindly searching for the solution. To avoid the disturbance of irrelevant sample points, only those points distributed within a specified buffer zone are adopted for fitting calculation. Figure 5 depicts the sample point  $T_{ij}$  and a  $w_{buffer}$  wide buffer determined by an edge  $\overline{v_m v_n}$  of the model. The suffix  $i$  is the index of edge line  $L_i$  and  $j$  is the index of sample points. Filtering edge pixels with buffer is reasonable, because the discrepancies between the bottom edges and the corresponding sample points should be small, as the model parameters have been fit approximately. However, the buffer size has to be carefully chosen because it will directly affect the convergence of the computation.

That the fitting condition we are looking for is the model edge exactly falls on the building boundary on the map. In Eq.(1), the distance  $d_{ij}$  represents a discrepancy between a sample point  $T_{ij}$  and its corresponding edge  $\overline{v_m v_n}$ , which is expected to be zero. Therefore, the objective of the fitting function is to minimize the squares sum of  $d_{ij}$ . Suppose an edge is composed of the vertices  $v_m(x_m, y_m)$  and  $v_n(x_n, y_n)$ , and there is an edge pixel  $T_{ij}(x_{ij}, y_{ij})$  located inside the buffer. The distance  $d_{ij}$  from the point  $T_{ij}$  to the edge  $\overline{v_m v_n}$  can be formulated as the following equation:

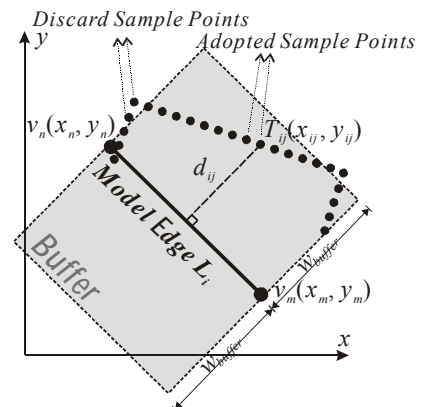


Figure 5. Buffer zone for fitting.

$$d_{ij} = \frac{|(y_m - y_n)x_{ij} + (x_n - x_m)y_{ij} + (y_n x_m - y_m x_n)|}{\sqrt{(x_m - x_n)^2 + (y_m - y_n)^2}} \quad (1)$$

The coordinates of vertices  $v_m(x_m, y_m)$  and  $v_n(x_n, y_n)$  are functions of the unknown plan parameters. Therefore,  $d_{ij}$  will be a function of the plan parameters. Taking a box model for instance,  $d_{ij}$  will be a function of  $w, l, \alpha, dX$ , and  $dY$ , with the hypothesis that a normal building rarely has a tilt angle ( $t$ ) or swing angle ( $s$ ). The least-squares solution for the unknown parameters can be expressed as:

$$\Sigma d_{ij}^2 = \Sigma [F_{ij}(w, l, \alpha, dX, dY)]^2 \rightarrow \min. \quad (2)$$

Eq.(2) is a nonlinear function with regard to the unknowns, so that the Newton's method is applied to solve for the unknowns. The nonlinear function is differentiated with respect to the unknowns and becomes a linear function with regard to the increments of the unknowns as follows:

$$0 + v_{ij} = \left(\frac{\partial F_{ij}}{\partial l}\right)_0 \Delta l + \left(\frac{\partial F_{ij}}{\partial w}\right)_0 \Delta w + \left(\frac{\partial F_{ij}}{\partial dX}\right)_0 \Delta dX + \left(\frac{\partial F_{ij}}{\partial dY}\right)_0 \Delta dY + \left(\frac{\partial F_{ij}}{\partial dZ}\right)_0 \Delta dZ + \left(\frac{\partial F_{ij}}{\partial \alpha}\right)_0 \Delta \alpha + F_{ij0} \quad (3)$$

in which,  $F_{ij0}$  is the approximation of the function  $F_{ij}$  calculated with given approximations of the unknown parameters. Given a set of unknown approximations, the least-squares solution for the unknown increments can be solved, and the approximations are updated by the increments. Repeating this calculation, the unknown parameters can be solved iteratively.

The linearized equations can be expressed as a matrix form:  $V=AX-L$ , where  $A$  is the matrix of partial derivatives;  $X$  is the vector of the increments;  $L$  is the vector of approximations; and  $V$  is the vector of residuals. The objective function actually can be expressed as  $q=V^T V \min$ . For each iteration,  $X$  can be solved by the matrix operation:  $X=(A^T A)^{-1} A^T L$ . The standard deviation of each increment can also be calculated as the accuracy index of the LSMDF.

The objective of the height fitting is the building's roof in the LiDAR data. As the distance from sample point to the edge is the observation function in the plane fitting, the observation function should be the distance from LiDAR point to the roof plane in the height fitting. The roof plane equation is composed of model parameters. However, the calculations of 3D fitting would be much more complicated than 2D. And it will also increase the iteration number and the chance to divergence. Considering the efficiency and the practicality, we adopt an easier method for the height fitting in this paper. Since the plane parameters have been fit optimally, LiDAR points within the plane range are supposed to belong to the model. These points are then projected to a local 2D coordinate system which is defined on the façade of the model. Fig. 6 illustrates the transformation of a ridge-roof building. Thus the observation function is simplified as the distance from 2D point to edge, similar to the plan fitting.

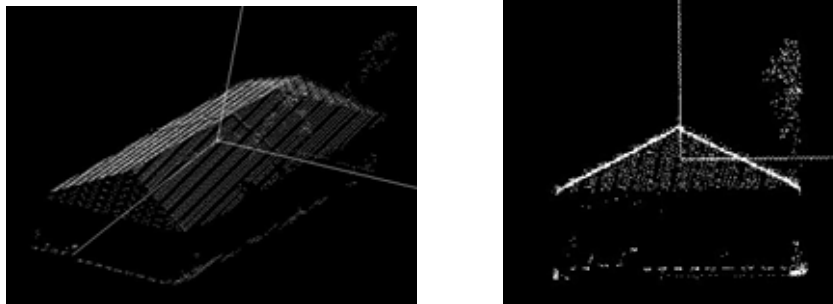


Figure 6. Projection of the LiDAR points for height Fitting.

## 4. EXPERIMENTS

A small urban area of Taipei City about 500*hectare* is selected for testing the proposed approach. The 1/1000 scale digital topographic maps have been pre-processed to generate building polygons. The grid interval of the corresponding DEM is 4*m*. The aerial photos are taken by the Vexcel UltraCam D photogrammetric camera. The focal length is 101.4*mm*, the image size is 7500\*11500*pixel*, and the size of a pixel is 9\*9*μm*. The average flight height is about 1930*m*, so the ground resolution is about 0.17*m/pixel*. Meanwhile, we develop a PC program by C++ language to implement the proposed building reconstruction procedures. The interface is illustrated by Fig. 7. The measuring sequence as follows: (1) observe the topographic map in the left window and select the appropriate model; (2) click vertices  $v_1$ ,  $v_2$ , and  $v_3$  in sequences on the topographic map to give initial parameters; (3) examine projections on photos and adjust the model parameters if needed; (4) click the Fitting button to implement LSMDF of plane and height optimal fitting; (5) examine projections on photos and adjust the model parameters if needed; (6) output and save the model parameters. A model is usually reconstructed within a minute, but the time for a building depends on its complexity. Fig. 8 shows an example of the reconstructed 3D models overlapped on DEM.

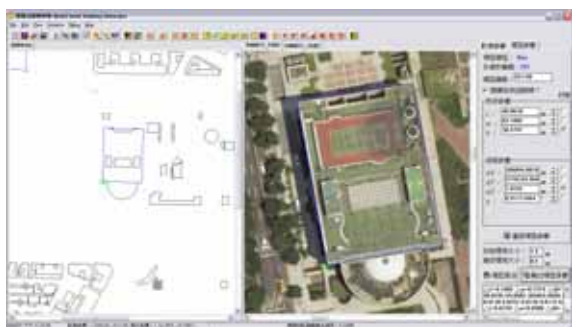


Figure 7. The interface of the MBBR program.

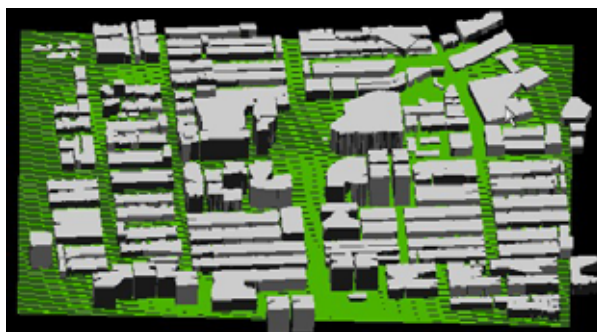


Figure 8. Reconstructed 3D models.

To verify the experimental accuracy of the reconstructed models, the vertices coordinates of 30 models are calculated from model parameters and then compared to the photogrammetric result. Table 1 lists the statistics of the coordinate differences. The larger  $X$ - $Y$  differences most due to the mismatch point, while the larger  $Z$  differences most due to the parapets.

Table 1. Statistics of coordinates differences

Coordinates Differences	$\Delta X$	$\Delta Y$	$\Delta Z$
Max. (m)	0.762	0.137	3.034
Min. (m)	-0.695	-0.492	-1.932
Avg. of Absolute (m)	0.120	0.083	0.799
Average(m)	0.014	-0.029	0.047
Std. Deviation (m)	0.2203	0.1256	1.0335

## 5. CONCLUSIONS

The floating model is proposed as a model-based building reconstruction approach, which is a flexible 3D measuring tool floating in the object space. This paper introduces one kind of its utilization for reconstructing models from different source data. Plan parameters are fit from topographic maps and height parameters are fit from LiDAR data and DEM. Aerial Photos are also used for examining and modifying. According to our practice in the case of Taipei City, the procedure goes smoother and faster with the increase of operating experiences. Here are some characteristics of the proposed approach:

1. For most of the normal buildings, floating model does increase efficiency than point-by-point measurement.
2. The labor-consuming precise measurement is carried out by computer while the operator only needs to select model and approximately fit it.
3. The inner constraints guarantees the geometric nature unchanged after reconstructing.

4. It is possible to reconstruct the whole building even if a part of it is occluded.

However, we also find some shortcomings of the model-based approach:

1. A building could never be reconstructed correctly if there is no adequate primitive model.
2. The decomposition of building needs practice and experience.
3. It is difficult to implement the subtraction operation between two models.
4. For those very complicated buildings, model-based approach will cost more time than data-based approach.

Therefore, we suggest two further research objectives: (1) designing more primitive models such as curvy plane. (2) analyzing the topology and implement the Boolean operator among 3D models.

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