Semi-automated Model-based Building Reconstruction by Fitting Models to Versatile Data

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ABSTRACT: *Model-based Building Reconstruction* (MBBR) is a convinced approach to reconstructing 3D building models by fitting pre-defined models to aerial photographs. In this paper, we proposed the *Floating Models*, which can be applied to versatile data, such as the topographic maps, LiDAR points cloud, aerial photographs and DEM, with the *ad hoc Least-Squares Model-Data Fitting* (LSMDF) algorithm. Floating models is a series of pre-defined primitive models which are floating in the space as the floating mark is. Each model is associated with a set of parameters that can be used to control its shape and pose. A building is reconstructed by adjusting these parameters so the wire-frame model adequately fits into the building's outlines among versatile source data. This model-based reconstruction provides better constraints to the shape of the model in contrary to the data-based approach. Since topographic maps and aerial photographs provide better accuracy in plane and LiDAR points cloud and DEM provide better accuracy in height, the fitting are separated for 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 building's boundaries based on the LSMDF algorithm. Third, the computer computes the roof or ridge height from the LiDAR points within the roof's boundary, and interpolates the datum height from DEM. Finally, the model parameters and standard deviations are provided and the wire-frame model is superimposed on all overlapped aerial photographs for manual checking. The operator can make any necessary modification by adjusting the corresponding model parameter. A 528-*hectare* urban area of Taipei City is selected for experimental tests. The corners' coordinates derived from fitting result are compared to the traditionally photogrammetric measurements. The experiment shows that most of the modern buildings can be modeled smoothly and the results achieve the accuracy as traditional Photogrammetry does.

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 Gülch, 1996; Grün, 2000; Lang and Förstner, 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; Böhm et al., 2000; Brenner, 2000; Das et al., 1997; Ermes, 2000; Tseng and Wang, 2003; van den Heuvel, 2000). *Model-Based Building Reconstruction*(MBBR)(Ameri, 2000; Brenner, 1999; Sester and Förstner, 1989; Wang and Tseng, 2004) starts with the hypothesis that a model is a representation of the target building in the object space, then verifies the correspondence between model and data sources, such as topographic maps, aerial photographs, LiDAR points cloud, and DEM. Since each kind of data sources has its own characteristics, the model could be fit to point, line segment, or surface, as Fig. 1 shows.

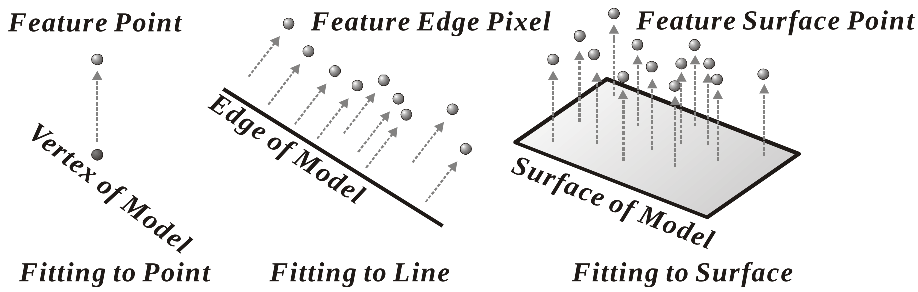


Figure 1. Fitting model to versatile data sources.

Inspired by the CAD-based Photogrammetry and MBBR, we proposed a naval measuring tool – *floating models* – for reconstructing 3D building from versatile data sources. The floating model represents a flexible entity floating in the 3D space. 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 control the volume along the pre-defined dimension. From the conventional 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 MBBR's point of view, floating mark is an exceptional case of floating model without any shape parameter. We proposed three kinds of floating models – box, gable-roof, and polygonal prism – for building reconstruction at the experimental tests.

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 information of a building is determined when model-data fitting achieves optimal. Therefore, the key of the automation is the algorithm able to determine model parameters of a floating model, such that the wire-frame model is optimally coincided with the corresponding building edges. 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 points cloud to derive height parameters. Finally, the wireframe model is projected onto aerial photographs for examining. The operator can make further modification of the model according to the photographs if necessary. Fig. 2 uses a box model as an example to depict the proposed reconstruction procedures.

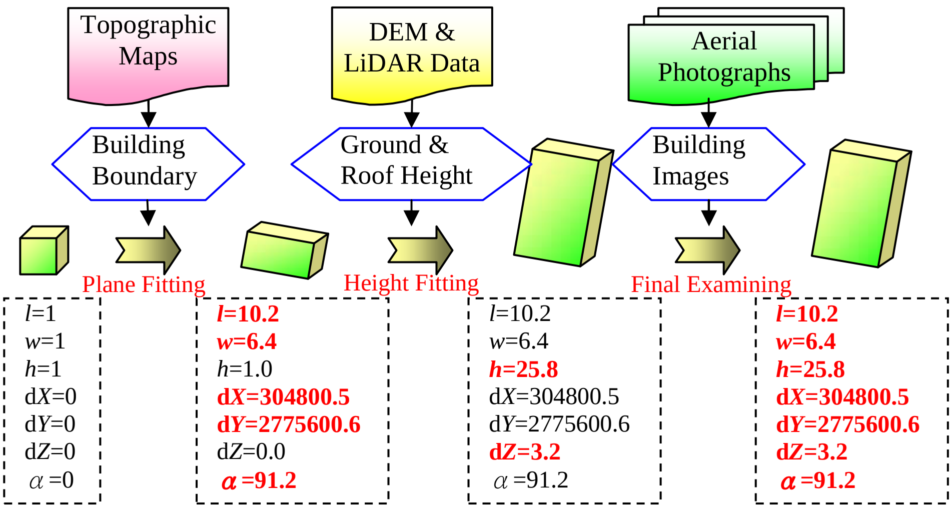
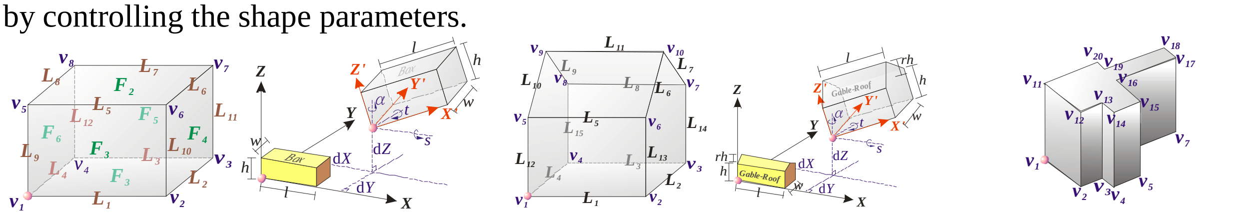


Figure 2. The flowchart of the proposed reconstruction procedures.

2. FLOATING MODELS

Conventional 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 occlusion or the shadow from other obstacles. With the increasing demands of 3D object models, this point-by-point procedure has become the bottleneck in production. To deal with the problem, we proposed floating models which complies with the constructive solid geometry. Each floating model is basically a primitive model, which determines the intrinsic geometric property of a part of building. The primitive model could be any kind of practical models as long as it can be defined and represented by parameters. For example, it could be the line segment, the rectangle, the circle, the triangle, the box, or 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 and pose 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 (α) around Z-axis to represent the rotation of a primitive model. 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 the topology and the model parameters of a box model, a gable-roof model, and a polygonal prism model. The X'-Y'-Z' coordinate system defines the model space and the 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 adjusting parameters. It is very clear that, the model is "floating" in the space by controlling these pose parameters, and the volume is flexible with certain constraints by controlling the shape parameters.



(a) Box Model (b) Gable-roof Model (c) Polygonal Prism Model

Figure 3. Topology and the model parameters of floating models.

3. LEAST-SQUARES MODEL-DATA FITTING

Since the topographic maps are plotted by photogrammetric means, its planar accuracy would be better than the LiDAR points cloud. On the contrary, the LiDAR point cloud and DEM provide better accuracy in height. 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.

3.1. Plan Fitting

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 erase elements not belong to any building and to establish the close-and-complete polygons instead of poly-lines. These pre-processed polygons are the bases of plane fitting. The operator selects an appropriate primitive model and adjusts it to approximately fit to the corresponding polygon. The 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.

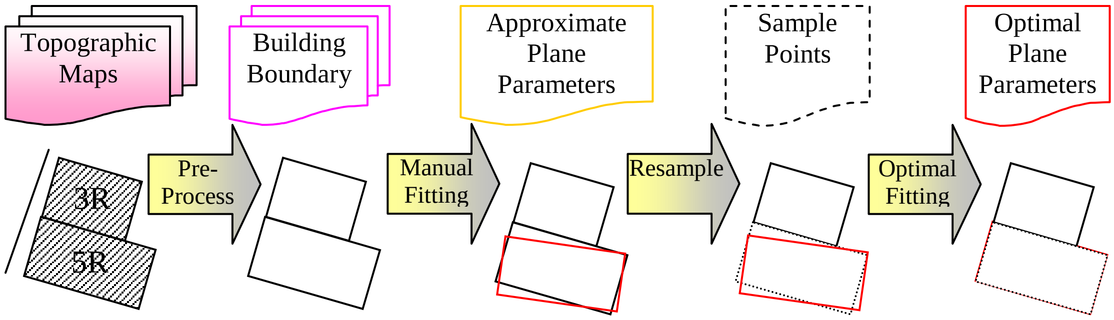


Figure 4. The flowchart of plane fitting.

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. The approximate plane parameters are taken as the initial values, so the LSMDF could iteratively pull the model to the optimal fit instead of blindly search for the solution. A specified buffer zone is set up to filter out irrelevant sample points. Fig. 5 depicts the sample point T_{ij} and the 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 when the model has been fit approximately.

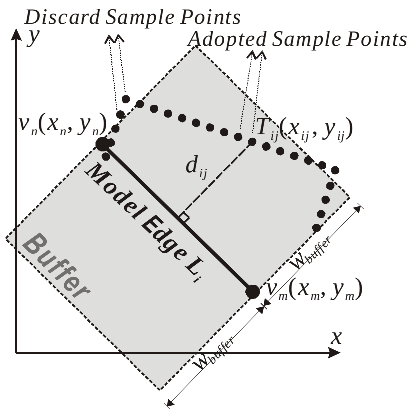


Figure 5. Buffer zone for fitting.

The optimal fitting condition we are looking for is that the edges are exactly falling on the building boundary. 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:

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

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, α, dX, and dY, with the hypothesis that a normal building rarely has a tilt (t) or a swing (s) angle. The least-squares solution for the unknown parameters can be expressed as:

$$\Sigma d_{ij}^2 = \Sigma[F_{ij}\,(w, l, \alpha, \mathrm{d}X, \mathrm{d}Y)]^2 \rightarrow min. \tag{2}$$

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:

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

in which, F_{ij0} is the approximation of the function F_{ij} calculated with given approximations of the unknown parameters. The linearized equations can be expressed as a matrix form: $\boldsymbol{V}=\boldsymbol{AX}-\boldsymbol{L}$, where $\boldsymbol{A}$ is the matrix of partial derivatives; $\boldsymbol{X}$ is the vector of the increments; $\boldsymbol{L}$ is the vector of approximations; and $\boldsymbol{V}$ is the vector of residuals. The objective function actually can be expressed as $q=\boldsymbol{V}^{\mathrm{T}}\boldsymbol{V}\rightarrow min$. After each iteration, $\boldsymbol{X}$ can be solved by the matrix operation: $\boldsymbol{X}=(\boldsymbol{A}^{\mathrm{T}}\boldsymbol{A})^{-1}\boldsymbol{A}^{\mathrm{T}}\boldsymbol{L}$. The standard deviation of each increment can also be calculated as the accuracy index of the LSMDF.

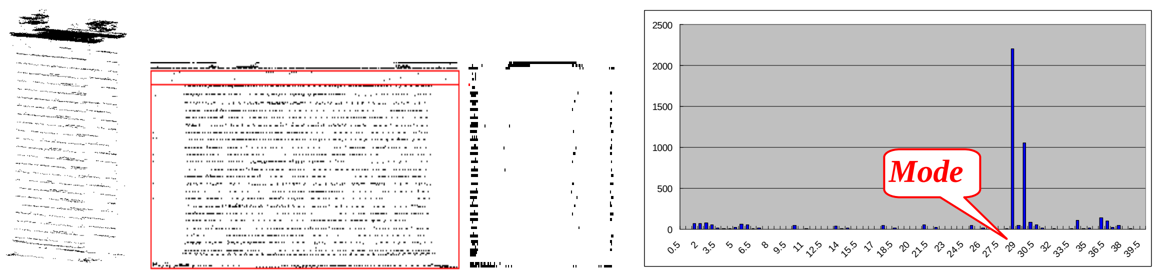


Figure 6. The LiDAR points cloud of a box building and the mode of height among all points.

3.2. Height Fitting

The objective of the height fitting is the building's roof in the LiDAR points cloud and the datum point in the DEM. Since the plane parameters have been determined optimally at the plane fitting stage, the location of the datum point and the planar range of the building are also defined. Thus, the height of the datum point could be estimated by 4 neighboring DEM grid nodes with the bi-linear interpolation. The building height (h) and the roof's height (rh) are determined by fitting model to LiDAR points cloud within the planar range of the building. For the flat roof model, such as box and polygonal prism, building height (h) is estimated by calculating the mode among all of the point's height, as Fig. 6 shows. For the gable-roof model, the LiDAR points cloud is transformed to a local coordinate system defined on the lateral side of the building, then the roof eaves are optimally fit to the points in buffer zone, as Fig. 7 depicts. With the coordinate transformation, the observation function of the height fitting is simplified as the distance from 2D point to edge, similar to the function of the plan fitting.

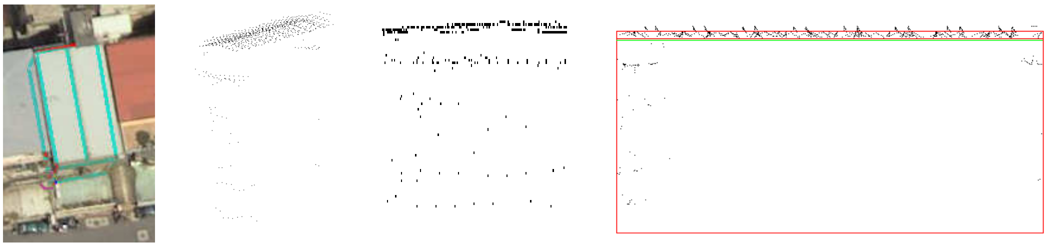


Figure 7. Fitting roof eaves to the LiDAR points cloud in a local coordinate system.

4. EXPERIMENTS

A small urban area of Taipei City about 528*hectare* is selected for testing the proposed approach. The 1/1000 scale digital topographic maps have been pre-proceeded to generate building polygons. The grid interval of the corresponding DEM is 4*m*. The aerial photos are taken by the Vexcel UltraCam D digital photogrammetric camera. The focal length is 101.4*mm*, the image size is 7500*11500*pixel*, and the size of a pixel is 9*9μm. 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. 8. By default, the computer will automatically generate polygonal prism model for all of the buildings on the map by fitting their roofs to LiDAR points cloud. Then, the operator can choose to delete or modify an existing model, or reconstruct a new model. Whether in the modifying or the reconstructing process, the LSMDF will automatically and optimally fit the model to versatile data sources. In such a semi-automated manner, a building model is usually reconstructed within a minute, but the time for the whole building depends on its complexity. Fig. 9 shows one sheet of the reconstructed 3D models.

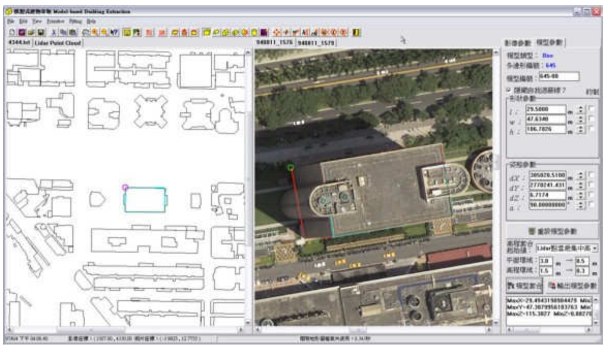


Figure 8. The interface of the MBBR program.

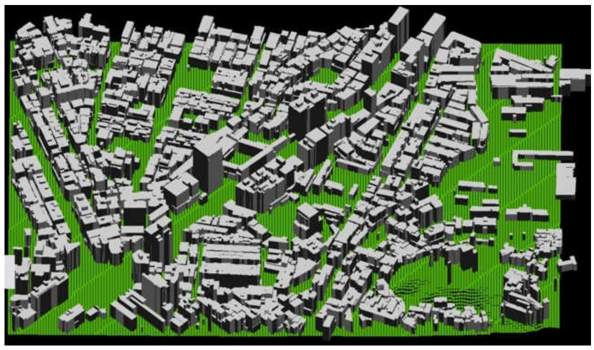


Figure 9. One sheet of reconstructed 3D models.

We select 38 buildings to test the proposed approach and verify the experimental accuracy. They are reconstructed by 94 boxes, 19 gable-roofs, and 104 polygonal-prisms. The vertices coordinates are calculated from model parameters. Meanwhile, there are totally 912 vertices measured by experienced photogrammetrist by conventional photogrammetric means as the ground truth (GT). Table 1 lists the analysis matrix of correctness and completeness.

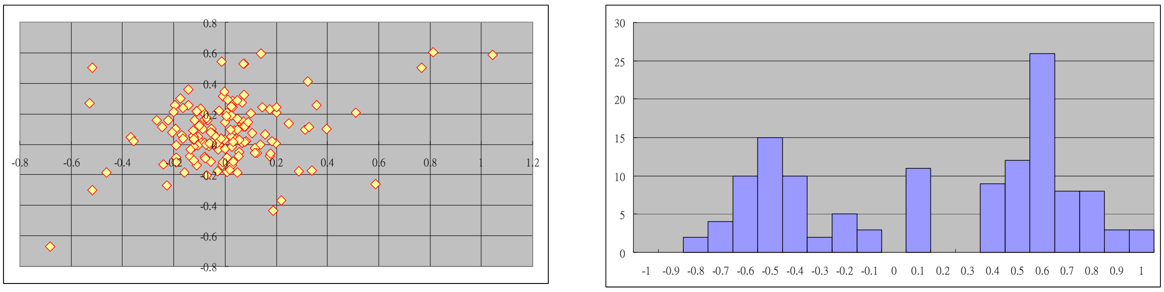
Table 1. Correctness and completeness analysis.

Photogrammetry / MBBR	True	False	Total	Commission (C/T)	Correctness (S/T)
True	623(S)	11(C)	634(T)	1.74%	98.26%
False	289(O)	N/A		Omission (O/GT)	Completeness (S/GT)
Total	912(GT)			31.69%	68.31%

Table 2. Statistics of the coordinate differences.

Differences	ΔX	ΔY	ΔZ
Mean (m)	0.0182	0.0524	0.2563
RMSE (m)	0.2115	0.2028	1.0572

The accuracy of MBBR is evaluated by comparing the vertices coordinates. Table 2 lists the statistics of the coordinate differences and Fig. 10 shows the distribution of plane differences and the histogram of the height differences.



(a) Plane differences distribution chart. (b) Height differences histogram.

Figure 10. Charts for coordinate differences.

5. CONCLUSIONS

A flexible 3D modeling tool called floating models is proposed for model-based building reconstruction. Along with the ad hoc least-squares model-data fitting algorithm, building models can be reconstructed semi-automatically among versatile data sources. Plan parameters are fit from topographic maps and height parameters are fit from LiDAR data and DEM. According to the case study, the MBBR procedure goes smoother and faster with the increasing of operating experiences. Some characteristics of the proposed approach could be remarked:

1. For most of the normal buildings, floating model does increase efficiency than point-by-point measurement.
2. The labor-consuming measurement is carried out by computer while the operator only has to select model and approximately fit it.
3. The inner constraints guarantees the geometric nature unchanged after reconstruction.
4. It is possible to reconstruct the whole building even if a part of it is occluded.
5. Floating models achieve similar accuracy as conventional photogrammetric measurements.
6. Although we fit model to versatile data sources in this research, floating model is also applicable to single data source.

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