REBUILDING THE 3D MODELS OF BUILDINGS BASED ON LIDAR DATA*

Shen Wei [1], Chen Yunhao [2], Li Jing [2], Siti Atikah [3], Nuradzri [3] LipHong Tay[4]
1.Ocean College of Shanghai Fisheries University, 334 Jungong Road, Shanghai, 200090, China
Tel: (0086) -13371935143 E-mail: wshen@shfu.edu.cn;
2.State Key Laboratory of Earth Surface Processes and Resource Ecology (Beijing Normal University),19 Xinjiekouwai Street, Beijing, 100875, China;
3. Malaysia Centre for Remote Sensing , No.13, Jalan Tun Ismail, 50480, Kuala Lumpur, Malaysia.

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ABSTRACT: LIDAR (Light Detection And Ranging) is one of the most effective remote sensing system, which could provide three dimensional information of earth surface with high accuracy and speed. The 3D building model rebuilding is the key problem for digital city construction all along. In this paper, Alpha Shapes algorithm and Delaunay TIN Decaying algorithm are developed to extract the building boundary, and then the 3D models of flat-roofed buildings are rebuilt by the boundary and average elevation. In addition, a clustering method based on normal vector and relevant regularization strategies are developed to rebuild several kinds of familiar non-flat-roofed buildings. The tests prove these algorithms are very suitable and effective for building rebuilding automatically based on LIDAR data.

1 Introduction

1.1 LIDAR System

LIDAR (Light Detection and Ranging) is a system which utilizes laser beam for detection and measurement. The whole system comprises of three state-of-art components, i.e. Laser, IMU (Inertia Measurement Unit) and GPS (Global Positioning System). These components are mounted on a jet or helicopter enabling DEM acquisition across the flight path to be performed accurately and rapidly. Several hours after data acquisition, various data includes DTM of the acquired area can be obtained. The data absolute accuracy can be up to 15 cm while relative accuracy is less than 5 cm with horizontal accuracy about 20 cm. In terms of speed, density and efficiency, LIDAR system is more superior than conventional surveying method. Therefore, airborne LIDAR system is becoming one of the most advanced tools in remote sensing industry, especially for urban 3D data acquisition.

LIDAR technology has been developed for more than 10 years. Currently, most of the technical issues about hardware and system integration are basically solved. Nevertheless, the data processing and software development are somehow slower and becoming a bottleneck of LIDAR technology development.

Buildings are the main element to form a city. The acquisition of 3D information and model development have becoming the major support and foundation for urban planning and management, climate study, environment conservation, disaster management, telecommunication network distribution, dynamic urban monitoring and urban spatial analysis and simulation. However, the complication of urban building shapes has caused huge difficulty for urban model rebuilding. Therefore, extraction and rebuilding of urban model form LIDAR data are the main difficult focuses in LIDAR data processing.

1.2 Urban 3D Model Development Methods

Building model is a shrunk model which represents the physical shape of a building. Currently, building model can be categorized into two major types, i.e. a) parametric model which is represented by building parameters to describe the building geometry; b) generic model which form using the flat or curve surfaces to describe the building and does not have fix shape(Förstner, W.,1999; Maas, H.,1999).

In reality, the classification and construction of the model are closely related. The model construction methods are:

1 Model-driven Methods

Model-driven method requires a model database which contains fix building models. While model rebuilding, the actual data will be compared with the existing model in the database in order to obtain the parameters from the existing model for model development (Haala, N.,1994). Mass and Vosselman(1999) had implemented invariant moments to reconstruct building model.

2 Data-driven Methods

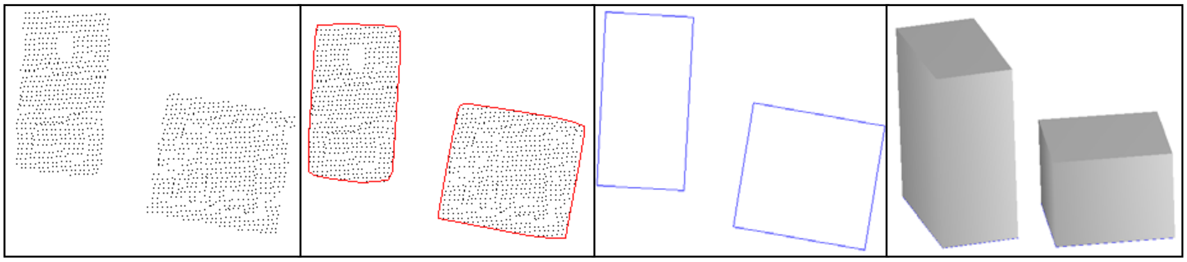
Data-driven model is normally used to process generic models. The pre-requisite is the building geometry can be defined by a series of flat or curve surfaces. This method comprises of three major steps: 1) Extracting the building surface, 2) Reconstructing the surface topology, 3) Reconstructing the building model. Because it doesn't require supposition and database of model, it is theoretically capable of describing every kind of buildings. However, due to the flexibility of this method, it causes a lot of difficulties during modeling.

Mass and Vosselman (1999) have described the data-driven method for model construction in their studies. They utilized Hough Transform to detect the building roof. Roof is also detected based on surface data calculation. Rottensteinar and Briese (Rottensteiner, F. ,2002) use the percentage of pointlike calculation to detect the surface sample area. Feature extraction method is also utilized to classify the pointlike points.

3 Constructive Solid Geometry Method (CSG)

CSG method seems to be a combination of both methods mentioned above. A complex building is separated into many small building elements. These elements are then stored in a building element database. The model is separated into several parts , and every part is compared and examined with building element in the database. Then the part is defined with corresponding parameters. The advantage of this method is a lot of building model can be represented with those models in the database. However the disadvantage is the separation of the building is normally quite difficult.

Due to the various types and complexity of building model, model-driven method cannot describe too many urban buildings. Therefore, this study utilizes data-driven method. The building will be classified based on roof slope and the models will be constructed individually. The building with roof slope lesser than 5 degree will be classified as flat roof building while the others will be classified as non-flat roof building. The LIDAR data (as depicted in fig1-a) used in this study has



(a) Extracted building laser points

(b) Building outline extraction

(c) Building outline normalization

(d) 3D building model construction

Figure 1: 3D Rebuilding of flat-roof building model

been filtered and extracted by filter algorithms. Then the building outline (as depicted in fig1-b) is extracted and normalized(as depicted in fig1-c) by several algorithms. At last, the 3D flat roof building model is rebuilded based on the building outline and elevation(as depicted in fig1-d). However non-flat roof building will be reconstructed based on the outline and its rebuilded roof.

2 Building Model Reconstruction of Flat-roof Building based on Building Outline

Most of the urban buildings are flat-roof building, besides common digital city application just require a simple models while neglecting the building roof. Therefore, most buildings can be simplified as flat-roof building which is rebuilded basically by outline and average height.

2.1 Building Outline Extraction

Building outline extraction is the foundation of urban mapping and 3D modeling which is becoming one of the major difficult topics in LIDAR data processing. Normally, the LIDAR point clouds are rasterized into gray level DSM. The generated DSM is furthered processed to obtain nDSM(normalized DSM). Image processing methods such as image classification or boundary line extraction together with high resolution images are utilized to extract building outline (Ma Ruijin,2004; Li Shukai,2000; Sohn G.,2003). Aiming at the current research actuality and requirements, this study developes two new methods for point clouds processing, i.e. 1) Alpha Shape method and 2) Delaunay Triangulation Decaying method.

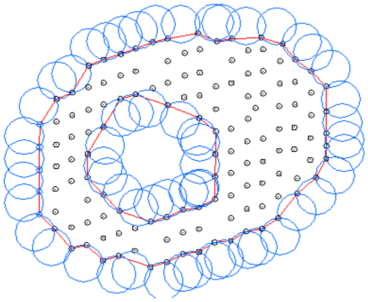
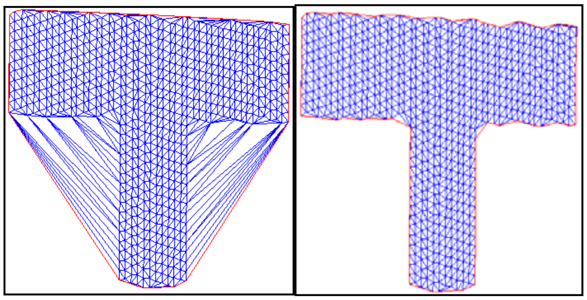


Figure 2: Alpha shape algorithm extraction principle



(a) (b)

Figure 3: The comparison between two TIN

2.1.1. Alpha Shape Method

A limited accumulated points S has an alpha shape in polygon. This polygon is determined by the accumulated points S and α. Imagine that a circle with an α radius is rolling around the S. When α is big enough, the circle won't fall into the area of accumulated point. The rolling track will form the boundary outline of these accumulate points. contrarily, when the α value is very small ($\alpha \to 0$), every point might be the boundary. When the alpha value is approaching infinity ($\alpha \to \infty$), alpha shape will be the convex hull(Nataraj Akkiraju, 1995). When the S containing evenly distributed points and α approaching optimum value, the alpha shape can extract the inner and outer boundary of the polygon at the same time as shown in Figure 2.

2.1.2. Delaunay Triangulation Decaying Method

Performing Delaunay Triangulation without restriction on point cloud of a concave polygon will result to a wrong building outline. From Figure 3-a, it was observed that the generated triangular network also covering the none building area. Based on Delaunay triangulation method without restriction, the Decaying algorithm will analyze the generated triangulation network and perform decaying process to eliminate the unnecessary triangles, at the same time correcting the outline of the polygon as depicted in Figure 3-b.

Based on the above analysis, the author has defined three decaying factors, i.e. area factor, perimeter factor and angle factor. After a mass of experiments, the decaying factors are determined as below:

1. any angle within the triangulation is greater than a predefined threshold, e.g. 150°.
2. any side length of the triangulation is greater than a predefined threshold, e.g. 2 times of the calculated average side length.
3. any triangulation area greater than a predefined threshold.

The triangulation generated by Delaunay triangulation method will be removed if accord with condition above.

2.2 Outline Normalization

The outline obtained from two methods above is very rough which can be define as raw outline. Raw outline usually is composed of zigzag shape along the derived outline as shown in Figure 2 & 3. The raw outlines are further processed using sleeve algorithm(Zhao Zhiyuan,2005)etc. which are based on the changes of angle direction to retrieve the polygon inflexion points. These inflexion points and retained while the intermediate points are eliminated. The remained inflexion points were thus simplified and formed a basic framework of the polygon. This study defined two normalization algorithms which can be applied for four sided and multi-sided polygon (greater than four side and the number of side must be even number):

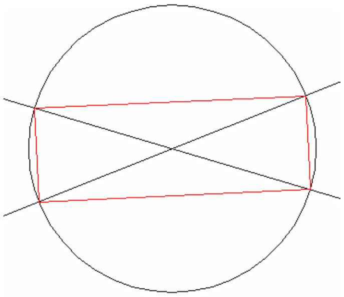
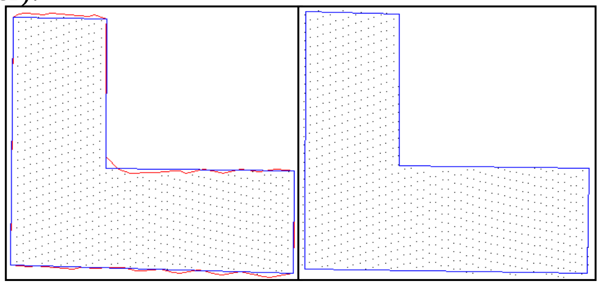


Figure 4: Circumcircle Regularization Algorithm Principle



(a) Raw outline (b) Optimized outline

Figure 5: Example of Cluster and Adjustment algorithm

2.2.1. Circumcircle Regularization Algorithm

As shown in Figure 4, two orthogonal line intersection of the wire frame (or the average value of four nodes) are identified. This intersection point works as the middle geometry point of the polygon and the circumcircle. After that, the furthest distance of the intersection point with the four nodes is identified as radius (or the average distance as radius) to draw a circumcircle. Four intersection points are identified between the circle and the two diagonal line and linking up the four points will result in a new rectangle.

2.2.2. Cluster and Adjustment Algorithm

This method includes clustering and adjustments. The procedures are as follow:

1. Find the azimuth angle of every outline and separate the boundary lines into type A & B based on the azimuth angle (Type A as building main direction and B for adjustment)
2. Calculate the average azimuth angle $\bar{a}$ for type A and B, Weighted average method can be applied to increase the calculation accuracy with length of boundary defined as weight. The algorithm is: $\bar{a} = \sum_{i=1}^{n} (a_i \times l_i) / n$.

3. The average azimuth angle of type A will remain while the average azimuth angle of type B will be adjusted based on type A and obtain a new type B average azimuth angle.
4. Adjust every boundary line by using the middle point as primary axis until they fulfill the new average azimuth angle. The intersection nodes are then identified.
5. These nodes are linked up to obtain an Regularized building outline as shown in Figure 5.

2.3 3D Reconstruction of Flat-roof Building

This kind of building can be reconstructed once the building outline is given a building height (an average height value from accumulated points of the building) and is shown in Figure 6. The advantage of this model is its relatively easier to be constructed and can be done using batch processing without human intervention. At the same time, most of the 3D modeling software can support this type of model.

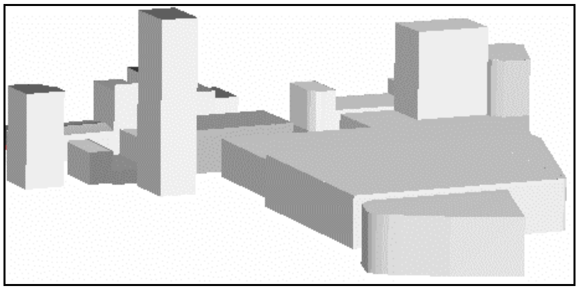
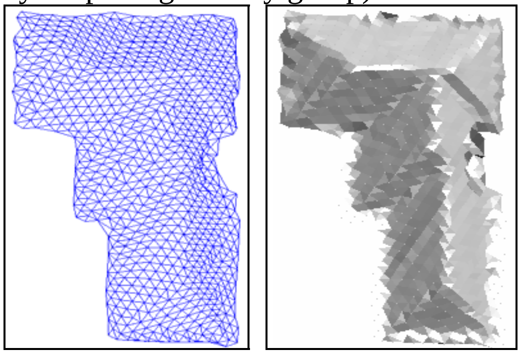


Figure 6: 3D reconstruction of flat-roof building

3 Building Roof Reconstruction using Delaunay Triangulation Irregular Network (TIN)

The reconstruction of building assumes that: every building has geometry which formed of flat or curve surfaces (or comprised of geometry shapes). Delaunay TIN method is a data-driven method for roof reconstruction. Theoretically, it can reconstruct any kind of roof shape. The effect is shown in Figure 7.

However, LIDAR data itself comprises of non uniform and scattered points. Due to data acquisition condition and other interference, the roof type generated from Delaunay TIN without any processing might result in a rough and distorted roof as shown in Figure 7. Therefore, the generated roof requires regularization, i.e, representing the roof using some linked regular geometry surface (or use regular geometry shape or geometry group).



(a) wireframe mode (b) Shade mode

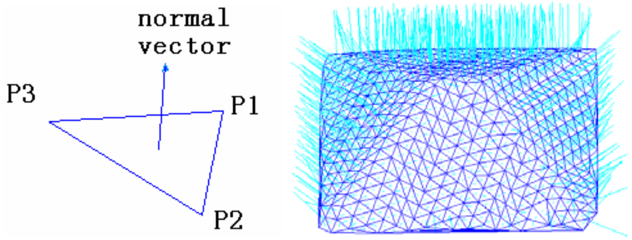
Figure 7: 3D Reconstruction of Roof based on Delaunay TIN

3.1 Roof Extraction using Normal Vector and Clustering Analysis

Regardless of shape or surface to represent the roof, we must know how many surfaces are required to describe the roof. We also need to identify whether the shape is a curve or flat surface, a triangle or rectangle.

The points or triangles on a same surface are related in certain aspects. By using these relations, clustering can be performed to group the points or triangles and thus obtain the characteristic information of the roof.

This study mainly focuses on the normal vector to group the triangles and obtain roof information. Flat surface normal vector is the vertical vector of a flat surface. The direction of normal vector follows the rule of right hand thumb. The normal vector for triangle, $P_1P_2P_3$ are shown as Figure 8-a. The normal vector of triangle, $P_1P_2P_3$ is in opposite direction.



(a) normal vector (b) Normal Vector clustering

Figure 8: Normal Vector of Triangle and its clustering

As shown in Figure 8-b, the normal vectors of triangles on same surface are mostly having the same direction. By using this factor, the triangles can be separated into a few groups. These groups which represent the surfaces are named as surface elements in this paper. If the distance factor is taken into consideration, the complex roof can be well clustered. A triangle with three top points, P1 *(x1, y1, z1)*, P2 *(x2, y2, z3)*, P3 *(x3, y3, z3)* and normal vector V_{P1P3} and V_{P3P2} can be represented as:

$$\begin{cases} V_{P1P3}=(x_1-x_3)i+(y_1-y_3)j+(z_1-z_3)k \\ V_{P3P2}=(x_3-x_2)i+(y_3-y_2)j+(z_3-z_2)k \end{cases} \tag{1}$$

The normal vector of the triangle, n can be defined as multiplication of two vectors on the same surface:

$$n = V_{P1P3} \times V_{P3P2} \tag{2}$$

When we combined (1) into (2), we can obtain the components of the normal vectors in three different axis directions:

$$\begin{cases} n_x = (y_3-y_1)\times(z_2-z_1)-(z_3-z_1)\times(y_2-y_1) \\ n_y = (z_3-z_1)\times(x_2-x_1)-(x_3-x_1)\times(z_2-z_1) \\ n_z = (x_3-x_1)\times(y_2-y_1)-(y_3-y_1)\times(x_2-x_1) \end{cases} \tag{3}$$

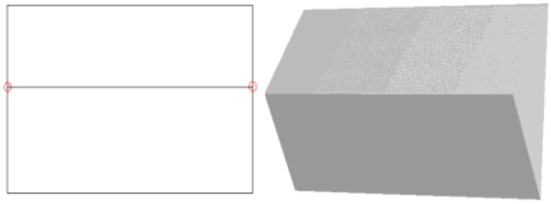
Unit normal vector $n_{x'}, n_{y'}, n_{z'}$ is utilized for real practice and drawing. Normal vector of triangle can also be described by two parameters: (1) the azimuth angle of projection geometry, α and (2) the included angle of normal vector and horizontal surface β:

$$\alpha = \begin{cases} \arcsin(\frac{n_{x'}}{\sqrt{(n_{x'}^2+n_{y'}^2)}}) \\ \arcsin(\frac{n_{x'}}{\sqrt{(n_{x'}^2+n_{y'}^2)}})+\frac{\pi}{2} \\ \arcsin(\frac{n_{x'}}{\sqrt{(n_{x'}^2+n_{y'}^2)}})+\pi \\ \arcsin(\frac{n_{x'}}{\sqrt{(n_{x'}^2+n_{y'}^2)}})+\frac{3\pi}{2} \end{cases} \qquad \beta = \arctan(\frac{n_{z'}}{\sqrt{(n_{x'}^2+n_{y'}^2)}}) \tag{4}$$

3.2 Normalization of Roof

1 Gable Roof

If the building outline is a rectangle with roof normal vector identified as two groups, this roof is categorized as gable roof. The key problem are outline and two points which are the intersection of the outline and the roof crest line, A&B as shown in Figure 9-a. By using two group of sides average normal vector and any point, we can obtain the two flat surfaces equations. From the join sides of both surfaces, we can also obtain the crest line equation and subsequently obtain the A&B plannimetric coordinate by project the crest line to the outline. The coordinate information are brought into the crest line equation to obtain the A&B's 3D coordinate. The 3D roof derived from the A&B points and outline is depicted in Figure 9-b.

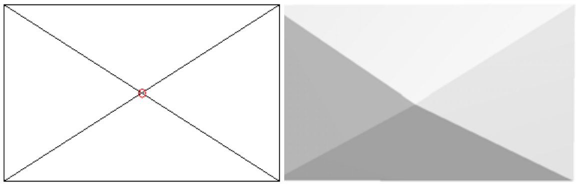


(a) (b)

Figure 9: 3D Reconstruction of Gable Roof

2 Pyramidal Roof

If the building outline is a rectangle, the normal vector of roof is separated as four groups and the numbers of triangle (or normal vector) are approximately same, then the roof is defined as pyramidal roof. The key problems of this model are the building outline and the top point A of the roof (adjoining point of four surface), as shown in Figure 10-a. Simply, the coordinate of centre point of outline can be assigned to point A and assign the highest Z value to the point A. The pyramidal roof constructed based on top point A and outline is illustrated in Figure 10-b.

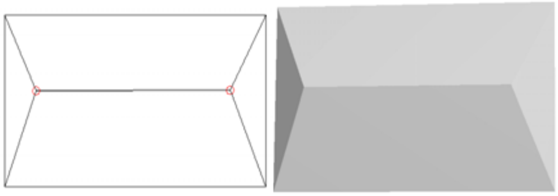


(a) (b)

Figure 10: 3D Reconstruction of Pyramidal Roof

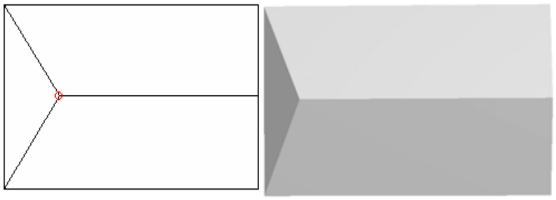
3 Transformation of Gable Roof

If the building outline is a rectangle with four groups of normal vector roof, while having different four group triangle integers (normally two groups are close while the other two are equal), then the roof is identified as gable roof transformation I, as shown in Figure 11.If the normal vector of roof is analyzed as three groups, then it is identified as gable roof transformation II, as shown in Figure 12.



(a) (b)

Figure 11: Gable Roof Transformation I



(a) (b)

Figure 12: Gable Roof Transformation II

The reasons of gable roof transformation are: the gable roof has two top points (Figure11), when the two points shifted horizontally, we will obtain gable roof transformation I as shown in Figure 11. If only one point has shifted, then we will obtain gable roof transformation II, Figure 12. If the two points has shifted until they merged as one, it becomes pyramidal roof. Therefore, any rectangle outline is actually formed by gable roof. Every model development will then focus on getting the two top points, A and B.

4 Conclusions and Discussions

4.1 The Pro and Con of Building Model Rebuilding using LIDAR Data

LIDAR system has the capability to obtain 3D information of urban feature with high speed, high accuracy, high density and lower cost. These advantages are those than can't be achieved by conventional surveying method. However, the airborne acquisition method has caused some natural limitations in its 3D data acquisition and model development:

1. Since it only contains roof top data, building with mix and complex shape cannot be reconstructed, e.g. the Kuala Lumpur tower which has bigger building on top and smaller underneath. The LIDAR data only can be used to reconstruct the upper part.
2. Due to high building's obstructing, some of the roof data are partially blocked and incomplete. This has caused difficulties to rebuild the whole structure.
3. Complex roof is difficult to be rebuilded.
4. The building boundary cannot be obtained directly and accurately, but only derived from indirect method.
5. The system accuracy and other parameters might affect the reconstruction accuracy.

These nature limitations can be solved by using various processing methods combined with other techniques, such as ground laser scanning system data to obtain detailed model, or utilize high resolution image to obtain building outline.

4.2 Accuracy Assessment of Model Reconstruction

Although there are many researches on 3D laser point clouds data processing, however there are very little studies which discussed about the accuracy of the reconstructed models. Some researchers pointed that (Zhang xiaohong,2006): the accuracy assessment of reconstructed building model should take the matching of the constructed model and raw point clouds data into consideration, which means the fitting accuracy. And not comparing the model with the actual building. This is an accuracy which reflects and focuses on the 3D model reconstruction. Since LIDAR data itself contains some natural limitations, the errors caused by the data itself might be bigger than the errors caused by the processing methods.

This study utilizes very high resolution satellite imagery (Quickbird) and ground survey building dimension data as main reference to conduct accuracy assessment on the reconstructed model. The analyzed data shown that the building outline extraction methods and 3D building roof reconstruction methods mentioned in this study can well guarantee the model accuracy (the difference between the model and actual measurement is normally less than 0.5 m). The error caused by the algorithms is proportional to the complexity of the building shape which is normally lesser than the data error itself (errors due to system error and data limitation).

The experiments prove that the algorithms mentioned in this study are effective and very practical in building modeling. These methods provide a good solution for LIDAR data processing and 3D urban model rebuilding.

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