CONSTRAINT-BASE LIDAR POINT CLOUD FITTING

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ABSTRACT

Airborne Light Detection and Ranging (LiDAR) has the ability of acquiring high-resolution and high-accuracy point clouds. The processing on point clouds has thus become an important research topic and has drawn increasing attention in the fields of remote sensing. An increasing number of 3D building models have been available in the Internet with the development of Web 2.0 techniques and scanning equipment. Many web-based data-sharing platforms, such as Google 3D Warehouse and MakerBot Thingiverse, provide functions for users to upload and share their models. Therefore, a fitting approach is proposed to construct building models using airborne LiDAR data. An iterative approach consists of three main parts, geometric analysis, point cloud segmentation, and model refinement, in proposed the experimental result shows that the proposed approach can generate 3D building models efficiently.

KEY WORDS: point cloud reconstruction, 3D building modeling, model refinement

1. INTRODUCTION

A model refinement approach is proposed to refine building models by using airborne LiDAR data. Point cloud reconstruction is important for building and city modeling with a variety of applications, such as urban planning, virtual tourism, computer game, 3D printing, real-time emergency response, and robot navigation. Traditionally, geometrical models are built up manually or processed by semi-automated and complicated procedures. It remains a very difficult and arduous task, especially when a large cityscape is required to be created. Many building models have been created and shared in www-based and model-sharing platforms. These user-created models have high-quality appearances. For example, Google 3D Warehouse (http://sketchup.google.com/3dwarehouse) and MakerBot Thingiverse (http://www.thingiverse.com/) are web-based data-sharing platforms which allows users to upload and share their models.

In this study, we propose a novel approach to refine building models by using airborne LiDAR data. The proposed approach is an iterative approach which can refine building models efficiently and accurately and avoid the nontrivial modeling procedures. Besides, geometric relationships and geometric constraints of the building model can be maintained.

2. RELEATE WORK

The major studies regarding point cloud modelling are reviewed in this section. The previous works about point cloud modeling can be classified into two categories (Ripperda and Brenner, 2009), *data driven* and *model driven*. The fundamental steps of data-driven methods are to segment a point cloud data into planes and combine these planes to a polyhedral model (Vosselman 1999, Rottensteiner 2003, Alharty and Bethel 2004, Bernardini et al., 1999). The advantage of these approaches is that they are useful in dealing with complex geometric shapes and details of buildings. However, the modeling quality may suffer from noises. Actually, noises are inherently present in point clouds. Therefore, this method is not suitable for LiDA data. The model-driven approaches reconstruct the point cloud data with the aid of template models. The advantage of model-driven methods is that they can maintain geometric relationships of a model, and also can reduce the effect of noise significantly. Tseng et al. (2003) and Chen et al. (2011) proposed template-based approaches by using numerical solutions. This study belongs to the model-driven category and the proposed method attempts to refine the building models by using point clouds.

3. METHODOLOGY

A model refinement scheme is proposed to deal with the differences between point clouds and building models. Most of the roofs of building models are constructed by planes. Therefore, our refinement scheme is based on plane fitting, that is, refine a plane by using its corresponding points. The goal of refinement scheme is to minimize the sum of distances between a point cloud and a plane. Figure 1 illustrates the workflow of the proposed approach which consists of three main procedures: geometric analysis, point cloud segmentation, and model refinement. In geometric analysis, the geometric relationships are established to constrain point cloud fitting. In the step of point cloud segmentation, echo point of point cloud is assigned to the corresponding surface of building model. These corresponding points are used in the surface refinement of building model. In the step of model refinement, the segmented point sets, geometric relationships and constraints are used in model refinement.

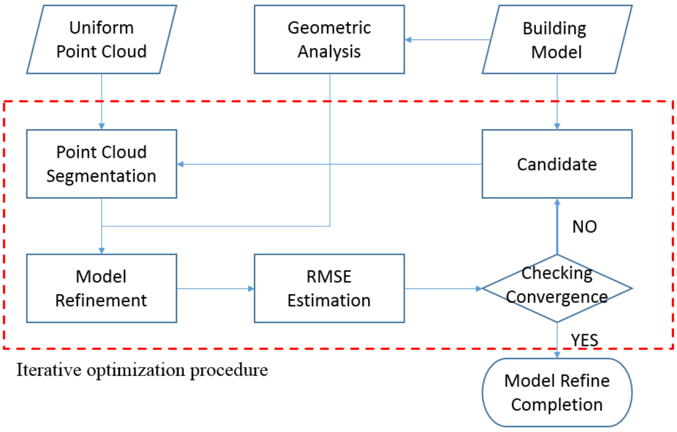

Figure 1. System Workflow. The proposed system consists of three main procedures, geometric analysis, point cloud segmentation, and model refinement.

3.1 Geometric Analysis

In previous studies, the process of plane fitting is to find a fitting plane that minimizes the sum of the squared Euclidean distances to a given point cloud. However, the geometric relationships of planes do not fully considered in the fitting process. In this study, the geometric analysis is performed to establish the geometric relationships of building model, including plane normal and angle. These geometric relationships are regarded as geometric constrains in the model fitting and refinement. Besides, these relationships are also used to reconstruct the surfaces of building model after the model refinement.

3.2 Point Cloud Segmentation

The proposed refinement approach is based on plane fitting that fits planes by their corresponding points. Region growing is a standard approach to segment the point cloud by using features, e.g., normal and curvature. However, these features are sensitive to noise. In this study, the point cloud is segmented by the surface of the input model. This approach assigns each point to the nearest surface. The nearest surface is determined by using Euclidean distance as follows:

$$d=\begin{cases} d_{per} & \text{, inside the polygon} \\ d_{poly} & \text{, otherwise} \end{cases}, \tag{1}$$

where d_{per} represents the perpendicular distance of polygon and d_{poly} represents the minimum distance between points and polygons.

3.3 Model Refinement

Our refinement procedure combines the geometrics relationships and the corresponding points to refine the building model. This procedure is inspired by plane fitting which minimizes the sum of the squared Euclidean distances to the given point cloud. For a plane, any point on this plane can be formulated as following equation:

$$f\left(x_i, \mathrm{y}_i, \mathrm{z}_i\right)=Ax_i+By_i+Cz_i+D=0, \tag{2}$$

where A,B,C are the plane's coefficients and represents plane's normal, and D/A represents the distance between the origin of coordinates and plane.

The algebraic distance of point (x_i, y_i, z_i) to the plane is formulated as:

$$\min\left(\sum_i f\left(x_i, \mathrm{y}_i, \mathrm{z}_i\right)^2\right)=\min\left(\sum_i(\mathbf{Da})^2\right), \tag{3}$$

where $\mathbf{D}=[x, y, z, 1]$ and $\mathbf{a}=[A, B, C, D]^T$ represents the plane's normal.

For two planes P and Q, they are formulated with eight unknown values:

$$\begin{aligned} &P: P_{n_x}x_i+P_{n_y}y_i+P_{n_z}z_i+D_1=0 \\ &Q: Q_{n_x}x_j+Q_{n_y}y_j+Q_{n_z}z_j+D_2=0 \end{aligned}, \tag{4}$$

where $P_{n_x}, P_{n_y}, P_{n_z}$ = the normal vector of plane P,

$Q_{n_x}, Q_{n_y}, Q_{n_z}$ = the normal vector of plane Q,

D_1/P_{n_x} = the distance between the origin of coordinates and plane P,

D_1/Q_{n_x} = the distance between the origin of coordinates and plane Q.

If P and Q have a known rotate angle θ in z axis direction, the normal vector $\left(Q_{n_x}, Q_{n_y}, Q_{n_z}\right)$ of plane Q can be rewritten as $\left(cos(\theta)\times P_{n_x}-sin(\theta)\times P_{n_y}, \sin(\theta)\times P_{n_x}+\cos(\theta)\times P_{n_y}, P_{n_z}\right)$ by a rotate angle

θ. The Eq. (4) can be rewritten as:

$$
\begin{aligned}
&P:\ \ P_{n_x}\times x_i+P_{n_y}\times y_i+P_{n_z}\times z_i+D_1=0\\
&Q:\ \ \left(\cos(\theta)\times P_{n_x}-\sin(\theta)\times P_{n_y}\right)\times x_j\\
&\quad+\left(\sin(\theta)\times P_{n_x}+\cos(\theta)\times P_{n_y}\right)\times y_j\\
&\quad+P_{n_z}\times z_j+D_2=0
\end{aligned}
\quad . \tag{5}
$$

By Eq. (3) and Eq. (4), the fitting planes of P and Q can be reformulated as following equation with a rotate angle θ in z axis direction:

$$
\min\left(\sum_i(\mathbf{Da})^2\right)=\min\left(\begin{bmatrix} p_{1_x} & p_{1_y} & p_{1_z} & 1 & 0\\ p_{2_x} & p_{2_y} & p_{2_z} & 1 & 0\\ \vdots & \vdots & \vdots & \vdots & \vdots\\ p_{k_x} & p_{k_y} & p_{k_z} & 1 & 0\\ U_1 & V_1 & W_{1_z} & 0 & 1\\ U_2 & V_2 & W_{2_z} & 0 & 1\\ \vdots & \vdots & \vdots & \vdots & \vdots\\ U_m & V_m & W_{m_z} & 0 & 1 \end{bmatrix}\begin{bmatrix} P_{n_x}\\ P_{n_y}\\ P_{n_z}\\ D_1\\ D_2\end{bmatrix}\right), \tag{6}
$$

where $j=1,2,3,\cdots,m$,

$U_j=\cos(\theta)q_{j_x}+\sin(\theta)q_{j_y}$,

$V_j=-\sin(\theta)q_{j_x}+\cos(\theta)q_{j_y}$,

$W_j=q_{j_z}$,

$p_i=$ corresponding point of plane P,

$q_j=$ corresponding point of plane Q.

In Eq. (6), a transformation scheme is adopted to solve the plane fitting problem of P and Q. This transformation scheme uses a community normal $\left(P_{n_x},P_{n_y},P_{n_z}\right)$, and regards the rotate angle θ as a geometric condition to transform the corresponding points of plane Q. By this transformation scheme, the geometric relationships of any plane can be extracted and regarded as geometric hard constraints. In Eq. (6), we instanced the rotate angle θ in z axis direction as a rotate example. In practical, to avoid the Gimbal Lock problem, the quaternion system is introduced to transform the corresponding points of every plane by geometric conditions.

Algebra least squares fitting (Pratt, V., 1987) is adopted to solve the minimize problem (Eq. (6)). By apply the Lagrange multiplier λ, the minimization problem can be transformed to a generalized Eigen-problem:

$$
\begin{aligned}
&\mathbf{D}^T\mathbf{Da}=\lambda\mathbf{Ca}\\
&\textit{subject to } P_{n_x}^2+P_{n_y}^2+P_{n_z}^2=1\ \ \textit{and}\ \ \mathbf{a}^T\mathbf{Ca}=1
\end{aligned} \tag{7}
$$

where $\mathbf{a}=\begin{bmatrix} P_{n_x} & P_{n_y} & P_{n_z} & D_1 & D_2\end{bmatrix}^T$,

$$\mathbf{C} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}.$$

For more details, please refer to the excellent survey (Chen et al., 2011). Finally, the solved coefficient vector *a* is used to reconstruct the surfaces of building model by geometric relationships.

3.4 Optimization

Each point of point cloud data is assigned to the nearest surface by using the distance function (Eq. (1)). However, some points near the corners of a building model may be assigned to incorrect surface. In order to avoid fail assignment, an iterative optimization procedure is adopted to segment the point cloud and refine the model. Especially the surface is not close to the point cloud. In the iterative optimization procedure, the surface of model would be refined repeatedly. After each refinement step, the surface is more close to the point cloud data, the point of point cloud would be re-assigned to the nearest and more correct surface.

4. EXPERIMENTAL RESULTS AND DISCUSSION

The proposed scheme that uses geometric hard constraints in building refinement is an extension of plane fitting. To demonstrate the robustness and feasibility of the proposed approach, we use a simulated data to verify the geometric hard constraints. In Figure 2, a scene is simulated to check our approach. Actual height of the building is 7 m, an existing building model height is 6 m (the blue model in Figure 2 Left). The newest point cloud data is used to refine the building model. The refined result is shown in middle of Figure 2. The point cloud is segmented to the nearest plane in different color, and the model height is also extended to 6.9983 m.

Besides, our approach is also compared with the standard fitting approach. Table 1 shows the comparison result of the proposed approach with geometric hard constraint conditions and standard plane fitting approach without conditions (Replace the model refinement in Figure 1). Those two approaches have similar results, e.g., the number of iterations, root-mean-square deviation (RMSE), width, length and height. However, the plane angles from standard plane fitting approach are not stable.

	Iteration No.	**RMSE(m)**	**Width(m)**	**Length(m)**	**Height(m)**	θ_1	θ_2	θ_3	θ_4
Our Approach	Initial	0.6743	4.0000	12.0000	6.0000	90.0000	90.0000	90.0000	90.0000
	1	0.0238	4.0035	12.0121	6.9978	90.0000	90.0000	90.0000	90.0000
	2	0.0237	4.0028	12.0082	6.9984	90.0000	90.0000	90.0000	90.0000
	3	0.0237	4.0028	12.0082	6.9983	90.0000	90.0000	90.0000	90.0000
	Iteration No.	**RMSE(m)**	**Width(m)**	**Length(m)**	**Height(m)**	θ_1	θ_2	θ_3	θ_4
Standard Plane	Initial	0.6743	4.0000	12.0000	6.0000	90.0000	90.0000	90.0000	90.0000
	1	0.0243	4.0024	12.0015	6.9978	90.0062	89.9938	90.0000	90.0000

Fitting Approach	2	0.0237	4.0041	12.0131	6.9983	90.0063	89.9937	89.9998	89.9998
	3	0.0237	4.0041	12.0081	6.9982	90.0063	89.9937	89.9998	89.9998

Table 1. Comparison between our approach and standard plane fitting approach.

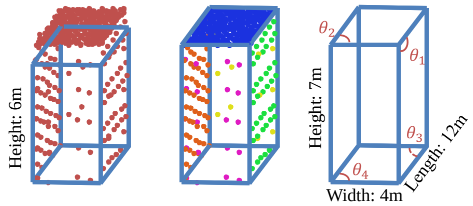

Figure 2. Experiment of simulated data. Left: simulated building model and its corresponding point cloud. Middle: result of model refinement. Right: illustration of geometric relationships ($\theta_{1\sim4} = 90$ degrees).

CONCLUSION

A model refinement method is presented to refine building models by using the newest point cloud data. The experimental results show that our approach can deal with multi-plane fitting by geometric condition transformation mechanism. In addition, the building models can be refined efficiently and accurately, and the original geometric relationships can also be maintained.

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