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# Boundary regularization of point clouds facades based on terrestrial laser scanning data

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**Abstract**: Traditional methods for boundary regularization mainly take airborne laser scanning (ALS) data as input and process the point clouds of building roofs with simple planar shapes, while terrestrial laser scanning (TLS) could acquire more complete and denser point clouds of building facades with more complex shapes. In this paper a new boundary regularization approach based on TLS data is proposed. It can deal with several types of point clouds for buildings facades, including walls, doors and windows. Firstly, raw point clouds are segmented into planar facades by using an efficient RANSAC algorithm. Secondly, the boundary points are extracted by using a 2D α-shapes algorithm. Based on the boundary points, a fitting regular polygon is generated by using the boundary regularization approach proposed in the paper. The experimental results show that the proposed approach is self-adaptive to point clouds with different density. Meanwhile, it is demonstrated that the approach is effective and efficient, and could provide reliable and satisfactory regularization results.

**Key words**: boundary regularization, point clouds, terrestrial laser scanning(TLS), building reconstruction
**PACS**: 42.79.Qx

# 基于地面激光扫描数据的建筑物边界规则化方法研究

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**摘要**:基于地面激光扫描数据,提出了一种新的建筑物边界规则化方法,不仅可以对建筑物整体而且可以对不同侧面进行规则化,包括立面墙面、门和窗户等.首先对海量原始激光点云利用高效的随机采样一致性算法分割为不同的平面面片,然后利用 2D α-shapes 算法提取建筑物点云数据.在此基础上,利用本文提出的边界规则化算法产生一个规则多边形进而实现建筑物边界规则化.利用实际地面扫描数据对该算法进行验证,表明本文方法可以针对不同密度的点云进行自适应调整,不仅效率高,而且可以达到非常满意的建筑边界规则化效果.该研究成果对于利用地面激光扫描数据进行建筑物三维建模具有一定的参考意义.

**关　键　词**:边界规则化;点云;地面激光扫描;建筑物重建

**中图分类号**:TN959.3　　**文献标识码**:A

## Introduction

Three-dimensional (3D) building model reconstruction from light detection and ranging (LiDAR) data is a hot research topic in recent years and has obtained promising results. Traditionally, the procedure for building reconstruction typically includes two key steps, i. e.,

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boundary segmentation and model reconstruction. The first usually takes the point clouds of building facades as input and extracts the boundary points of the facades, including internal and external points. Then the fitting lines are extracted by employing some fitting methods and the best fitting regular polygon would be generated by regularizing these lines. The result of boundary regularization may influence the quality of building model reconstruction greatly and directly. There exist two key factors affecting the boundary regularization results. One is the quality of raw point clouds, such as the density and accuracy, and obviously, point clouds with high density and accuracy can produce better results. The other is the data processing approach for boundary regularization. To process different sources of point clouds (ALS or TLS) and to get different features, for instance, roofs, walls and windows with different levels of details, the approaches of boundary regularization should be self-adaptive to raw point clouds data with different attributes to some degree. However, most literatures have concentrated on ALS data for reconstruction of buildings with planar roofs[1], while a few studies from the literatures have used TLS data for reconstruction of complex facades[2]. Peter and Nobert[3] generated building roof outlines by applying the 2D $\alpha$-shape algorithm, and the generation of boundary line segments is determined by the angular direction deviation of subsequent linear components. The orientation of the longest boundary line segment is taken as the initial orientation and other line segments are adjusted to be parallel or orthogonal to the initial one. Zhou and Neumann[4] rasterized roof points projected to one plane and constructed a closed boundary by analyzing topological relationships of these grids. Then the tangent directions of all boundary points were calculated and the principal directions were found by statistical analysis methods. By snapping to principal directions and neighboring segments, the closed and regular roof boundaries could be generated. Sampath and Shan[5] extracted boundary points using a modified convex hull algorithm for boundary tracing and proposed a hierarchical regularization method, in which two principal mutual perpendicular directions were determined by the relative long line segments, and the slopes of all other line segments were taken as weighted approximations to regularize them. Pu[6] took building outline generation as a process of polygon fitting plus knowledge-based occlusion assumption, and by applying the least square method or Hough transform, the fitting polygons could be achieved. These fitting polygons are classified into several categories, including walls, extrusions, roofs, windows and doors by calculating their geometric features. Different regularization methods were implemented based on prior knowledge.

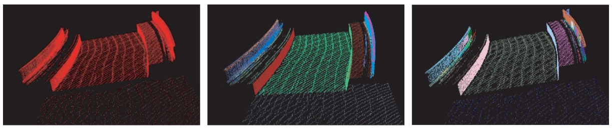
The aim of this paper is to reconstruct regular, closed and accurate polygons from facades point clouds based on TLS data. First of all the reconstruction workflow and relevant algorithms are introduced in detail (Introduction). Then the major two steps, segmentation and boundary regularization, are introduced (Sect. 1 ~ 2). Especially the boundary regularization algorithm proposed in this paper is illustrated step by step and validated by experiments (Sect. 2). Experimental results have demonstrated that the approach proposed in this paper is effective and efficient (Sect. 3). In the conclusion the advantages and disadvantages are summarized and the direction for further research is discussed (Sect. 4).

# 1 Boundary points segmentation

## 1.1 Segmentation

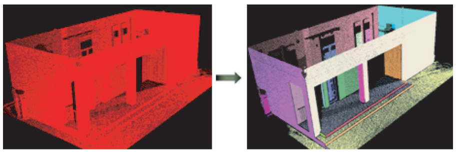
The raw point clouds of buildings are normally an ensemble with huge volume data. The first step of model reconstruction is to segment them into pieces of planar facades. Segmentation methods could roughly be divided into two categories[7], those that segment point clouds based on criteria like proximity of points and/or similarity of locally estimated surface normal, and those that directly estimate surface parameters by clustering and locating maxima in a parameter space. Region Growing is a classical segmentation algorithm of the former, which originates from region growing in digital image processing. Rusu[8] calculated normal and curvature of each point by its adjacent points and clustered them from the point with the lowest curvature, and took the deviation of normal and curvature of neighboring point as criterion to cluster or not. Similarly, the surface growing algorithm[7] adds several parameters to the processing procedure of region growing, such as proximity of points, locally planar and smooth normal vector field, and uses them as constraint criteria. It is more suitable to segment planar surface[9]. And the TIN (Triangulated Irregular Network) segmentation algorithm based on Region Growing describes primitive element with TIN and extracts surface by the adjacent triangle plane function[10]. The RANSAC[11] (RANdom SAmple Consensus) algorithm is capable of extracting a variety of primitive shapes from point clouds, which could be applied to clustering point clouds facades by surface parameters, and is one of the classical segmentation algorithms of the latter. Seq-NV-RANSAC (Sequentially-Normal Vectors-RANSAC) algorithm[12] checks the normal vector (NV) between the existing point clouds and the hypothesized RANSAC plane, and repeats the process sequentially and automatically until no planar surfaces can be extracted after extracting the first plane, and improves the segmentation quality and prevents noise. The Efficient RANSAC[13] improves the original RANSAC algorithm greatly, which adopts a localized sampling strategy and a score evaluation function and makes the processing procedure of segmentation effective and efficient. Especially in clustering planar facades, the primitive shape is only simply surface and the parameters of its equation could be calculated by three points which are sampled randomly. And the score evaluation function could take the percentage of points closed to the surface function as the evaluating indicator. And the localized sampling strategy is based on data organizing method of octree which could improve the efficiency of the segmentation procedure greatly.

This study uses the Region Growing algorithm and Efficient RANSAC algorithm to segment raw point clouds. Figure 1 shows segmentation results of a bridge using the two algorithms. Figure 2 is the segmentation result of total point clouds of a building using Efficient RANSAC algorithm.



(a) (b) (c)

Fig. 1 Segmentation results of two algorithms (a) raw point clouds, (b) region growing, (c) efficient RANSAC
图 1 两种算法分割结果(a) 原始点云,(b) RG 分割结果,(c) ER 分割结果



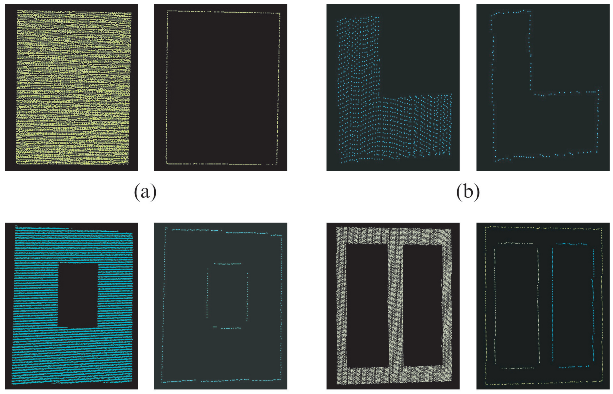
(a) (b)

Fig. 2 Segmentation results of applying Efficient RANSAC algorithm on total point clouds of a building (a) raw point clouds, (b) efficient RANSAC
图 2 应用 Efficient RANSAC 对建筑物所有点云进行分割的结果(a) 原始点云,(b) ER 分割结果

### 1.2 Boundary points extraction

Once the raw point clouds being segmented into different pieces of facades, the next step is to extract boundary points from these facades. Many approaches from the literatures have been proposed for boundary tracing (i. e. Convex hull, Delaunay triangulation, etc.), and some improved or new algorithms are proposed recently. Sampath[5] proposed a modified convex hull algorithm, which can detect the most adjacent points to the left-most point, and find a compact boundary finally. However, it can only extract external boundary points and do nothing for internal ones. Pu[14] constructed a TIN (Triangulated Irregular Network) firstly, and extracted the external boundary or inner boundary according to the length of TIN edge, while the threshold of the edge length is hard to set. Joaquin[15] extracted contour points by setting threshold of the edges of the triangulation, and speed up the procedure by classify point clouds into detail and facade layer using index of points density and area. Boulaassal[16] calculated the PCA (Principal Components Analysis) by the points of the planar cluster and set up a new coordinate system before constructing Delaunay triangles, and extracted external and internal boundary points from the long sides of triangles. Similarly, the tough problem is how to get the threshold. Shen[17] introduced a new algorithm called α-shapes to extract boundary points. Its principle can be described briefly that a circle with a radius of α is rolling around the point clouds, and the rolling track would be exactly the boundary of the point clouds if α is properly defined. Alpha shapes algorithm is suitable to extract the inner and outer boundary points, but the result is sensitive to α value.

This study adopts α-Shapes 2D algorithm to extract boundary points and modifies the output to separate internal and external boundary points for further processing. Figure 3 shows the experimental results of boundary extraction using α-Shapes 2D algorithm, and Fig. 3 (a) ~ (d) are for datasets with different boundary characteristics.



(a) (b)

(c) (d)

Fig. 3 Experiment results of boundary extraction using α-shapes 2D algorithm
图 3 应用 α-shapes 2D 算法边界点提取实验结果

## 2 Boundary regularization

Based on the extracted boundary points, a strict workflow is developed to generate fitting and regular polygon. Figure 4 shows the flowchart of the workflow of boundary regularization. Firstly, a best fitting plane is generated from the discrete boundary points which are already coplanar roughly. Secondly, all fitting line segments would be derived based on the fitting plane. And then some long line segments which lack points would be broken by connectivity analysis. Finally by adjusting these derived discrete lines to be parallel or orthogonal, an accurate, regular and closed polygon would be generated.

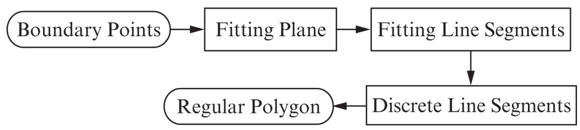



Fig. 4 Flowchart of boundary regularization approach
图 4 边界规则化流程图

### 2.1 Fitting plane

Point clouds of facade are coplanar after segmentation roughly, but not coplanar exactly. To get an accurate regular polygon, the best fitting plane of the facade should be extracted firstly. The authors propose a new approach which combines RANSAC algorithm with least square method. Given a surface could be constructed by three points which are not co-linear, three points are sampled randomly to construct fitting surface. And the plane equation constructed by the three points shows in Eq. 1 where $(A, B, C)$ is the normal of the plane.

$$Ax + By + Cz + D = 0 \quad . \quad (1)$$

And the distances of all points to the plane could be calculated using Eq. 2, where distances of points belong to different sides of the plane is considered with signal (usingsgn function).

$$\mathrm{Dis}_1 = \frac{\mathrm{sgn}(Ax_1 + By_1 + Cz_1 + D) \times |Ax_1 + By_1 + Cz_1 + D|}{\sqrt{A^2 + B^2 + C^2}} \quad . \quad (2)$$

Equation 3 calculates the average value of distances of points to plane.

$$\mu = \sum_{i=1}^{n} \mathrm{Dis}_i / n \quad . \quad (3)$$

The standard deviation of these distances is easily obtained too by Eq. 4.

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\mathrm{Dis}_i - \mu)^2} \quad . \quad (4)$$

By setting threshold of maximum of sampling times and/or minimum standard deviation, the best fitting plane would be generated finally.

### 2.2 Fitting line segments

Based on the extracted plane, all points projected on it will be coplanar accurately. Similarly the approach for extracting fitting line segments combines RANSAC algorithm with least square method. Two different points are sampled randomly to construct a line and count points that are close to the line and the threshold of distance is related to the density of point clouds. Equation 5 shows the line equation constructed by the two points, where $(A,B,C)$ is the direction of the line and $(x_0, y_0, z_0)$ is one point on the line. And Eq. 6 shows the computational formula of distance of point to line.

$$\frac{x - x_0}{A} = \frac{y - y_0}{B} = \frac{z - z_0}{C} \quad , \quad (5)$$

$$\mathrm{Dis}_i = \left| \frac{(x_i - x_0, y_i - y_0, z_i - z_0) \times (A,B,C)}{\sqrt{A^2 + B^2 + C^2}} \right| \quad . (6)$$

Giving threshold of distance of point to line for close points and threshold of the amount or percentage of closed points, fitting line segments could be extracted quickly. And the best line segments could be also extracted by applying least square method to the points close to the fitting line segments, which is just like Sect. 2.1 and using Eq. 3 and Eq. 4.

### 2.3 Discrete line segments

Figure 5(a) is a special case of fitting line segments that one single fitting line segment is extracted and the points are co-linear but discontinuous. There should be two discrete line segments in fact. So the component analysis needs to be implemented to discretize the long fitting line segment which has not continuous points. Figure 5(b) shows the result of component analysis. Additionally, the threshold in analyzing connectivity of fitting line segments is also relative to the density of point clouds closely.

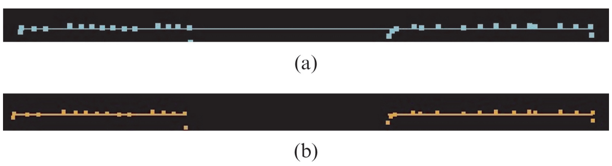


Fig. 5 The discretization of line segments by component analysis (a) Fitting line segment before component analysis, (b) Fitting line segments after component analysis

图 5 连通性分析离散化线段拟合(a) 分析前,(b)分析后

### 2.4 Regularization polygon

In order to get a closed and regular polygon, a new regularization method is deployed based on these discrete line segments. Firstly, the principal direction is determined according to the longest line segments. And all the other lines segments are adjusted to be parallel or orthogonal to the principal direction. To connect these adjusted lines segments to generate a closed polygon, most of them need to lengthen or shorten so as to obtain a closed polygon. Also there are some complex cases in regularization procedure which need to adjust automatically, including deviation, redundancy, lacks of line segments, etc. Figure 6 lists several typical cases in regularizing line segments.

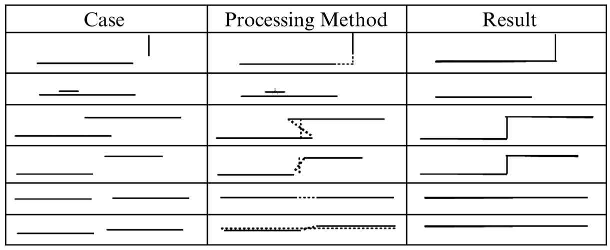



Fig. 6 Regularization results under different cases and with different processing method

图 6 几种典型情况的规则化处理方法及结果

An excellent algorithm should be robust and be adaptive to different data. In the processing of regularization presented in this paper, there are several key thresholds including standard deviation, distance buffer, edge length, connectivity, etc. And almost every threshold is related to the density of raw point clouds closely. So the density of raw point clouds is calculated firstly and the thresholds related to it are determined automatically after that. And the proposed approach in this paper is robust and self-adaptive to point clouds with different density.

## 3 Experimental results

To demonstrate the effectiveness and robustness of the approach of this paper, experiments dealing with different types of facades and qualities of point clouds are used. Figure 7 lists five typical situations of facades and experimental results. Figure 7(a) is a normal rectangle facade with high density point clouds, Fig. 7(b) is a L-type facade with sparse point clouds, Fig. 7(c) is an irregular facade whose boundaries are not mutual parallel or orthogonal accurately, Fig. 7(d) is a facade of wall with a window in the center, while Fig. 7(e) is a window with two panes of glass. In the last column of Fig. 7 the standard deviation of distance of contour points to fitting polygon are calculated. And all these experimental std are less than 1cm except Fig. 7(c) because its original data quality is poor and a big adjustment is implemented by the processing procedure. The experiment results indicate high precision of the proposed approach.

## 4 Conclusions and discussions

The goal of boundary regularization proposed in this paper is to provide some closed, regular and accurate polygons for building reconstruction. And it also has been demonstrated that the approach proposed in this paper is effective and efficient and could produce reliable and satisfactory regularization results, especially for facades with rectangular walls, windows, doors, etc.

Comparing to similar regularization methods such as

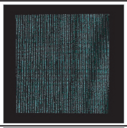
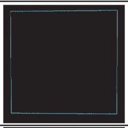
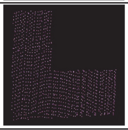
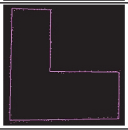
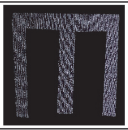
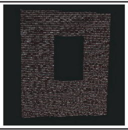
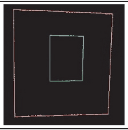
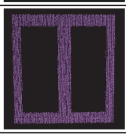
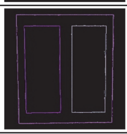
| | Raw facade | Regular polygon | Std(m) |
|---|---|---|---|
| (a) |  |  | 0.002 0 |
| (b) |  |  | 0.003 8 |
| (c) |  |  | 0.017 9 |
| (d) |  |  | 0.001 8 |
| (e) |  |  | 0.008 0 |

Fig. 7　Experimental results of boundary regularization
图 7　边界规则化实验结果

Convex hull algorithm[5], Knowledge based method[14] and single α-shapes algorithm[17], approach proposed in this paper is more effective and intelligent, and could get accurate facades polygons of building walls, windows and doors without constrained knowledge in advance. And this approach is more suitable to process TLS data particularly.

Obviously the proposed approach still cannot process complex shapes of facades such as curve walls and/or windows, complex protrusions of buildings because the RANSAC algorithm adopted in this paper only take surface as the primitive shape. To reconstruct more accurate model of building, these complex shapes should be taken as primitive shapes too, and this is an important direction for further investigation[18], and methods for reconstructing complex objects should be used for reference[19]. So the next step of boundary regularization study is to improve the approach and process more complex shapes of point clouds facades. In addition to data-driven approach proposed in this paper, model-driven approach for 3D reconstruction based on TLS data is also a worthy research direction. Additionally, TLS cannot get whole data sets of building sometimes because of scanning method or original building such as historical relics, so intelligent algorithm for such data need to be developed too[20].

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