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ABSTRACT

Lidar is a remote sensing technology that uses laser beams to generate high-accuracy, three-dimensional (3D) information of the Earth. As urban areas are developing and expanding rapidly, lidar applications such as 3D building modelling and city mapping are of increasing importance. Hence building boundary extraction is one of the main applications of lidar in civil engineering and urban planning projects. In this paper, three boundary extraction algorithms including an alpha-shape algorithm, a modified concave hull algorithm and a grid-based algorithm are tested to assess their object-by-object accuracy. The alpha-shape algorithm generates reliable boundaries for most of sample buildings, while the grid-based algorithm shows less consistency in some cases. The concave hull algorithm performs moderately with a few limitations. Advantages and disadvantages of each algorithm are identified and addressed in this paper.

1. INTRODUCTION

Lidar is an active remote sensing technology that emits laser beams to detect distant objects and measure ranges. Airborne lidar has been widely used since the early stage of the technology development (Wehr and Lohr, 1999). Lidar is of advantage for rapid and accurate vertical measurements at a relatively low cost; thus it shows strength in large-scale mapping and data acquisition of ground surface such as city mapping and Digital Elevation Model (DEM) generation. In addition, lidar is also widely applied in feature extraction due to the high density and vertical accuracy of the data.

Urban areas are of increasing importance in most of the countries since they have been changing rapidly over time. Buildings are the main objects of these areas, and building boundaries are one of the key factors for urban mapping and city modelling. Accurate building extraction using lidar data has been a prevalent topic that many research efforts have been contributed to. However, the complexity of building shapes and irregularity of lidar point distribution make the task difficult to achieve. Although there are plenty of algorithms trying to solve the difficulties, it is not feasible for a single method to fit for all. Each can perform well under a certain situation and requirement only.

In this paper, several building boundary extraction algorithms including an alpha-shape algorithm, a grid-based algorithm, and a concave hull algorithm are assessed. The strengths and limitations of each algorithm are identified and addressed. The point cloud used in this research is derived from the airborne lidar data acquired over the main campus of the University of New South Wales (UNSW) Australia in 2005.

Typically, the boundary extraction algorithms are applied to the clusters of building points when lidar data is segmented and classified. Many approaches have been attempted to improve the extraction algorithms. The simplest way to extract a rough boundary is using the convex hull method which has been implemented by several researchers (Qihong et al., 2008). However, this algorithm only fits for buildings with regular convex shapes. In order to overcome the limitation of this method many researchers have modified and improved the algorithm and obtained more reliable boundaries (Sampath and Shan, 2007). Another prevalent and recent method is to use an alpha-shape algorithm based on two-dimensional Delaunay Triangulation (Verma et al., 2006; Wei et al., 2011). This method works for both concave and convex shapes, and even for some complicated shapes. Another approximation-based algorithm was introduced by Zhou and Neumann (2008) using watertight grids.

Although it is observed that the aforementioned algorithms work well in different scenarios, a quantitative comparison analysis on each algorithm's performance on an identical dataset is rarely reported. Aiming at evaluating and improving these algorithms, we implemented a mathematical framework to compare the algorithms on an object-by-object basis. This study compares the boundary points selected by different algorithms and the impact of the selection on the accuracy.

2. BUILDING BOUNDARY EXTRACTION ALGORITHMS

2.1. Alpha-Shape Algorithm

The alpha-shape algorithm applied to the boundary extraction is based on the 2D Delaunay Triangulation. The boundary derived by this algorithm is always a subset of the Delaunay Triangulation of the point set (Edelsbrunner and Mucke, 1994). For a set of points, the alpha-shape algorithm draws and moves circles of a radius α towards the point set, and assign two points as boundary points if the two points touch the edge of a circle at the same time and no other point lies within the circle as illustrated in Figure 1. When the radius α is close to 0, every point would be a boundary of itself. On the other hand, when α is approaching to infinity, the boundary will be the convex hull of S. Thus, if a suitable α value is chosen, detailed inner and outer boundaries will be extracted. Generally, an α value larger than the average point spacing L and less than $2L$ is preferred (Wei et al., 2011). In this research, an optimal α value that matches this criterion is chosen.
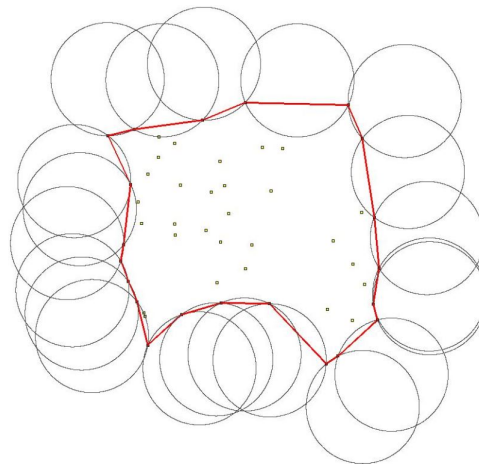

Figure 1. An illustration of the alpha-shape algorithm

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2.2.   A Grid-Based Algorithm

A grid-based algorithm is proposed by (Zhou and Neumann, 2008) based on the work of (Oliver et al., 2006) and (Verma et al., 2006). In principle, a uniform and watertight fishnet is applied to a 2D plane with all points within the cells. For every cell containing points, each side that does not overlap with others is regarded as an initial reference boundary. Then the points within the cell that are closest to the side are extracted as boundary points as illustrated in Figure 2. The cell size of the fishnet is the only control value for this algorithm and we believe that a value that makes the average point number in a single cell between 13 and 15 performs well for most cases. However, it can be seen from Figure 2 that some points may locate outside the extracted boundary. Therefore, the effect of these missing points will be demonstrated in this paper.
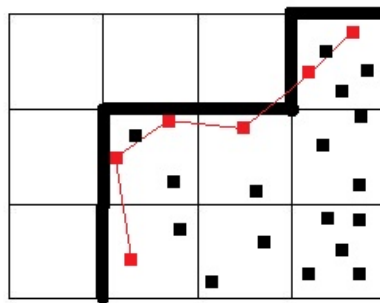

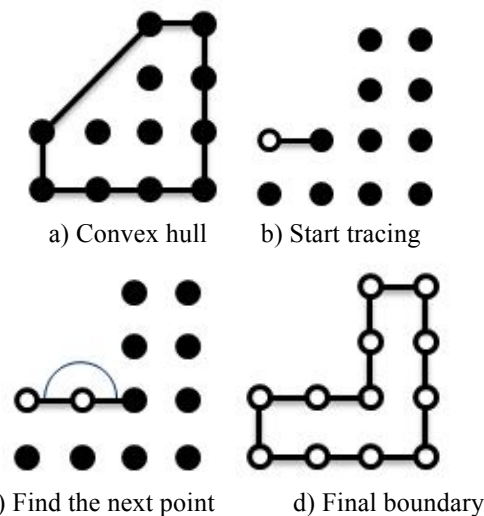**Figure 2. An illustration of the grid-based algorithm**

a) Convex hull   b) Start tracing

c) Find the next point   d) Final boundary

Figure 3. An illustration of the modified convex hull algorithm

2.3.   A Modified Convex Hull Algorithm

This algorithm was proposed by (Sampath and Shan, 2007) based on the general convex hull algorithm. A search radius is added to the original method as a control value. For a set of irregularly distributed points the convex hull cannot represent the actual shape formed by these points properly (Figure 3a). In the modified algorithm, after the first boundary point (usually the left-most point) is selected, only the points within a certain distance are considered in the boundary tracing process (Figure 3b). In this process, the point with the smallest clockwise angle to the previous boundary point is picked to be the next one (Figure

3c). Comparing to the original convex hull algorithm, the modified convex hull algorithm provides a more reasonable boundary as seen in Figure 3d.

3. RESULTS

In this research, three algorithms mentioned in the previous section are tested with the last returns of lidar data over the UNSW campus. The average point spacing of the lidar data is 1.15 m, while the vertical accuracy is 8 cm. In total, 8 building-point clusters are extracted from the lidar data (Figure 4). The extraction method is based on the principle that points belong to the same building must cluster and have similar height. Most of the trees are removed using the last return points.
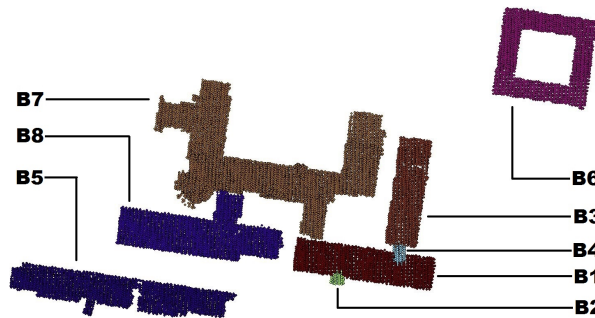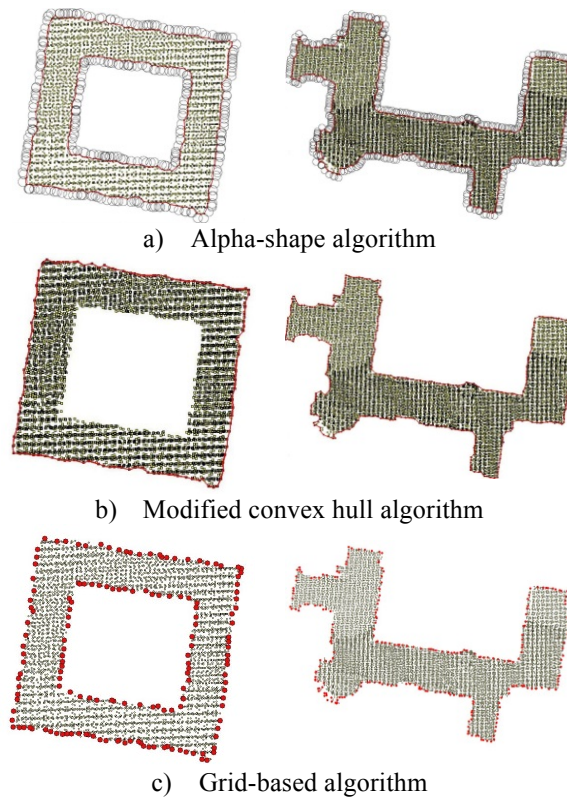
Figure 4. Distribution of building-point clusters

a)   Alpha-shape algorithm

b)   Modified convex hull algorithm

c)   Grid-based algorithm

Figure 5. Extraction results

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3.1 Boundary Extraction

The extracted boundaries of various types of building shapes are shown in Figure 5 where red points and lines represent the building boundaries. The radius α used in Figure 5a is 1.5 m which is between the average point spacing L=1.15 and $2L$. The cell size used in Figure 5b is 3 m, which makes the average point number in a single cell between 13 and 15. The search radius used in Figure 5c is set to be 2α. It can be seen that all three algorithms work well for both convex and concave shapes. However, the modified convex hull algorithm fails to extract the inner boundary of buildings.

3.2 Assessment

Although there are many researches on developing new algorithms and improving existing ones, few have compared the performance of these algorithms. Our accuracy assessment depends on many factors such as the accuracy of lidar data, the accuracy of reference data, the classification quality, and the performance of extraction algorithms. Moreover, due to the limitation of a lidar system the errors caused by the system may become larger than the errors generated in the processing steps. Therefore, this research focuses on the difference between the extracted boundaries instead of the absolute accuracy of the algorithms. A modified object-based evaluation method based on (Awrangjeb et al., 2010) is proposed for this comparison. Instead of the evaluation between extracted boundary polygon and reference polygon used in (Awrangjeb et al., 2010), evaluation between extracted boundary points and reference polygon is applied. The reference polygons are extracted from a high-resolution aerial image acquired over the UNSW campus in 2002.

Table 1. RMSD of the distances from the extracted boundary points to reference polygon (unit in m)

	B1	B2	B3	B4	B5	B6	B7	B8
Alpha-shape	1.24	1.10	0.50	0.78	1.12	1.13	1.16	1.09
Modified convex hull	1.30	1.19	0.58	0.78	1.29	0.99	1.25	1.14
Grid-based	1.36	1.12	0.60	0.85	1.27	1.14	1.17	1.06

Table 2. Standard deviation of the distances from the extracted boundary points to reference polygon (unit in m)

	B1	B2	B3	B4	B5	B6	B7	B8
Alpha-shape	0.84	0.56	0.39	0.49	0.99	0.88	0.95	0.82
Modified convex hull	0.84	0.48	0.42	0.49	1.11	0.78	1.01	0.84
Grid-based	0.83	0.49	0.46	0.47	1.10	0.90	0.97	0.79

Root Mean Square Difference (RMSD) is calculated and shown in Table 1 since the main focus is to compare the difference rather than the absolute accuracy. Table 2 shows the standard deviation of the distance from extracted points to the reference polygons. It can be seen from Table 1 that all three algorithms can generate similar results for simple convex building shapes (Buildings 1-4). For concave building shapes (Buildings 6-8), the modified convex hull algorithm produces boundary with a significant difference to others. Building 6 results in a smallest RMSD. However, this is due to the missing inner boundary points.

Comparing the results from the alpha-shape algorithm and the grid-based algorithm, it can be seen that the missing points from the grid-based algorithm (see Subsection 2.2) do not affect the accuracy much. However, for some complicated building shapes such as Building 5,

the grid-based algorithm shows an inconsistency due to the impact of the missing points. A more suitable cell size is suggested to resolve this problem. Since the alpha-shape algorithm performs consistently for all sample buildings, it is considered a suitable algorithm for most of the general extraction work. However, the efficiency of this algorithm is questionable when dealing with a huge dataset of high density since it will extract every possible boundary points. In that case, a grid-based algorithm with a large cell size can be used for initial extraction, followed by the alpha-shape algorithm.

4. CONCLUDING REMARKS

In this paper, three algorithms for building boundary extraction are assessed in an object-by-object basis. The alpha-shape algorithm generates reliable boundaries for most of sample buildings, while the grid-based algorithm shows a little inconsistency in some cases. The concave hull algorithm performs moderately with a few limitations. The alpha-shape algorithm is suggested for general building boundary extraction for its consistency and reliability. Future work is required to increase the efficiency of the alpha-shape algorithm because the basic principle of alpha-shape formation is to extract every possible boundary points which can be redundant for a high-density dataset.

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