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Upward-fusion urban DTM generating method using airborne Lidar data

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ABSTRACT

Airborne Lidar (Light detection and ranging) is an efficient tool for the generation of Digital Terrain Models (DTMs). Although many studies have been conducted in generating DTMs using Lidar data, it is still a challenging research area. The difficulty in filtering large buildings as well as a diversity of urban features makes the design of urban DTM generating methods an ongoing priority.

This research adopted an upward-fusion methodology to generate urban DTMs using airborne Lidar data. Firstly, several preliminary DTMs of different resolutions were obtained using a local minimum method. Next, upward fusion was conducted between these DTMs. This process began with the DTM of the largest grid size, which was treated as a trend surface. A finer DTM was compared with this large scale DTM. By setting appropriate thresholds, a new DTM was achieved by selecting qualified elevation values from the finer DTM and retaining the value of the trend surface when the value from the finer DTM was beyond the threshold. This process continued iteratively until all preliminary DTMs had been included in the upward fusion and a refined DTM of high resolution was achieved. To further reduce possible errors in the resulting DTM, an extended local minimum method was proposed for filtering outliers and generating preliminary DTMs.

A case study was carried out in the city of Cambridge, which represents an urban landscape with a variety of building forms, street patterns and vegetation structures. The time efficiency, results of the accuracy assessments and comparison with leading software proved the success of the case study and indicated that upward-fusion was an effective method for the generation of urban DTMs with airborne Lidar data and could improve the accuracy of other DTM generating algorithms. This paper also proposed possible approaches for further improvements on this methodology.

1. Introduction

Airborne Lidar (Light detection and ranging) is an emerging technology that obtains elevation information of surface targets by calculating the time of flight taken for laser pulse travel between a LiDAR sensor and a target scene. Relying on the accuracy of GPS and IMU components in the system, Lidar can produce data of high resolution and accuracy in both horizontal and vertical directions. With this information, researchers can analyze tree volumes, building structures and create 3D urban models. Although applications of Lidar data vary, all these modelling tasks are built around one indispensable procedure: generation of Digital Terrain Models (DTMs) from raw Lidar point cloud.

A Lidar point cloud is a set of points associated with *x*, *y*, *z* positional information. These points include ground points (signals returned from the terrain) and non-ground points (signals returned from objects such as trees and buildings). Elevation information from the whole point cloud, both ground points and non-ground points, forms a Digital Surface Model (DSM) whilst elevation information from ground points forms a DTM. Since ground points are mixed with non-ground points in the point cloud, processing algorithms are needed to generate DTMs from DSMs.

The use of local minima is the basis for one of the most widely used approaches for DTM construction from Lidar data. In this method, the lowest point in a moving window is assumed to be a ground point. By moving this window across the study area, one ground point can be selected in every cell and a DTM can be established with position information from these minimum points. The method works well in flat terrain with few trees and buildings, but struggles to achieve the balance between fine resolution (requiring a small window size) and little chaos (requiring large window size to deal with large buildings) from non-ground points. This problem has attracted significant attention and many attempts have been made to generate more accurate DTMs. Kraus and Pfeifer (1998, 2001) designed an algorithm based on robust linear prediction which has been widely accepted

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by researchers. Firstly, a rough approximation of the surface is computed using some local lowest points. Next, the residuals, (oriented distances from the surface to the measured points) are calculated and each point is given a weight according to its residual. Points with high weight will attract the surface whilst points with low weight will have little influence on the run of the surface. The process of weight iteration continues until a stable surface is acquired or the maximum number of iteration is reached. Some other methods have also been coined following the principle of refining the DTM step by step (Pfeifer et al., 2001; Elmqvist, 2002; Wack and Wimmer, 2002; Hu, 2003). Vosselman (2000) proposed a filtering method based on mathematical morphology and preserved terrain information by analyzing elevation differences among neighbouring points. This method was varied by Sithole (2001) and Roggero (2001a). To reduce the influence of relief, Sithole (2001) introduced a local operator which can alter parameters as a function of the slope of the terrain whilst Roggero (2001a) considered local morphology by setting the value of terrain parameters. Another emerging research topic is to derive a DTM with the help of a triangulated irregular network (TIN). Axelsson (2000) established a TIN with local minimum points and analyzed the relationship between residual points and the TIN. If a residual point meets certain criteria, it is included in the TIN to refine it. To avoid edge cutting effect, a method of mirror points is used to keep qualified edge points. Following the procedure, all ground points can be added to the final TIN. Sohn and Dowman (2002) adopted 'downward and upward divide-and-conquer triangulation' strategy to refine DTM iteratively. Firstly, a coarse TIN surface is established with some pre-selected ground points. Then 'Downward divide-and-conquer' is conducted to find points lower than the trend surface and update the TIN model using these new ground points. Next, 'Upward divide-and-conquer' is conducted to examine the spatial relationship between the rest of points and the TIN model. A hypothesis model is adopted to find candidate ground points which can be added into TIN surface and divide local area into more planar terrain surface. When more than one candidate point exist for a planar terrain surface, Minimum Description Length Criterion (MDL) is used to decide the most reliable points. This iteration continues until no new ground points can be added into the TIN model. Segmentation and classification are also important tools for derivation of DTMs (Roggero, 2001b, 2002; Lohmann, 2002; Nardinocchi et al., 2003; Brovelli et al., 2004; Tovari and Pfeifer, 2005; Sithole and Vosselman, 2005). By putting points from the original point cloud into different categories according to classification rules, ground points can be chosen to establish the DTM. Bartels and Wei (2006a, 2010), Bartels et al. (2006b) designed an unsupervised Lidar filtering algorithm – Skewness Balancing. This method only calculates the skewness value of the remaining point cloud and removes the highest point in the point cloud if the value is greater than 0. As a result, Skewness Balancing is a threshold-free algorithm, unlike most known filtering methods. Yao et al. (2008) and Bao et al. (2008) also employed Skewness Balancing and further developed this algorithm.

Since many algorithms were developed to extract DTM from point clouds, Sithole and Vosselman (2003) designed a comparative study to evaluate the performance of these methods under different circumstances. The sample data and results of this study are available for researchers' reference at http://www.itc.nl/isprswgIII-3/filtertest/index.html.

With the development of Lidar application, some specific software has also been developed to assist users to process Lidar data. Toolbox for Lidar data Filtering and Forests Studies (Tiffs), Terrascan, Lasground, SCOP++ and so forth, are designed to filter point cloud, generate DTM, and extract useful information from Lidar data. Based on classifying ground and non-ground points, this type of software can produce high quality DTM automatically.

Generating DTMs from Lidar data has thus been widely researched. However, generation of DTMs, urban DTMs in particular, is still challenging (Vu et al., 2004). Many DTM generating algorithms works efficiently in forest or suburb area, but will not work well in urban areas due to the existence of particularly large and flat-topped buildings. In addition, the requirements for DTM quality vary for different applications. For instance, landscape ecologists may need Lidar generated DTMs to assist their research whilst they have no access to commercial Lidar processing software and do not necessarily want to conduct complex programming to realize above-mentioned algorithms (very few DTM generating methods have been integrated into common GIS software). As a result, although existing algorithms are all based on rigid mathematical principles and apply well under certain situations, it is still important to design simple and effective methods for the generation of high resolution and accurate urban DTMs.

To meet these requirements, this research proposes an upward-fusion method to generate qualified DTMs in urban areas using airborne Lidar data. The method generates accurate DTMs efficiently and can easily be realized using standard GIS tools.

2. Methodology

Because of its simplicity and efficiency in terms of processing time, the local minimum method is widely used by researchers who would like to use DTMs as research sources but do not have access to complex and often expensive DTM generation software. However, when applied to urban areas, this approach has its limitations. If the moving window size in the method is not big enough, the lowest point in a cell will have a significant probability of being returned from a large building or tree, whose area can cover several cells. Nevertheless, if the moving window size is set very large (e.g. 50 m) to minimize the influence of non-ground points, the resolution of the DTM will be relatively low with excessive smoothing and will not provide sufficiently accurate information for further study, such as classification and modelling. To solve the problem, Zhang et al. (2003) filtered non-ground point using gradually increased window size and a constant slope operator that was decided by comparing the filtered and unfiltered data iteratively. Chen et al. (2007) adopted increased window size and a building mask to iteratively update the elevation of each point in the point cloud. Both researches achieved satisfactory results. Nevertheless, due to the existence of various urban features, the strict setting of slope operator and the building mask to filter very large buildings may result in some small features remained in the output DTM. In addition, the required programming work to implement these algorithms can cause difficulties to some researchers.

To easily obtain a satisfactory urban DTM, a raster-based upward-fusion algorithm is proposed to achieve accuracy as well as simplicity and efficiency. The principle of this method can be described as follows:

2.1. Generation of preliminary DTMs

The local minimum method can obtain qualified DTMs with high efficiency. However, some issues exist that may produce errors in the process of DTM generation. Generally, the main inaccuracy in the process is caused by points which have a much lower elevation value than their surrounding neighbours. For example, there may be low-lying ground with a small area but a large height difference located in a large scale cell. If one or more Lidar points are returned from this area, the elevation of the points from the