A slope- and elevation-based filter to remove non-ground measurements from airborne LIDAR data

Xuelian Meng

Geography department of Texas State University, San Marcos

601 University Dr ELA #391, San Marcos, TX 78666-3609

xm1001@txstate.edu

Abstract

This paper proposes a new slope- and elevation-based filter (OTFL) to extract the ground points from airborne LIDAR data. The filter applies a multi-directional scanning technique to label the ground points based on the slope change and the elevation difference to the nearest labeled ground points. This filter also considers the local elevation difference to prevent the accumulated errors. The identified ground points in the former scanning directions remain in the label of the next scanning direction, allowing the filter to utilize the former results and increases the chances of finding a nearer ground point.

The paper compares the performance of this OTFL filter with the one-dimensional and bi-directional scanning (OBL) filter. The quantitative error analysis based on the smaller study site shows that the OTFL filter improve the accuracy from 94.7891% to 97.3969%, and the Kappa values increase from 0.8918 to 0.9463. The OTFL filter can apply a smaller and suitable maximum elevation threshold, which is critical when applied in high-relief areas. The experiments prove that the OBL

filter is vulnerable to the selection of scanning directions and the distribution of the objects, which is improved by the OTFL filter. The OBL filter fails with larger areas on small hills, whereas the OTFL filter generates better results without obvious errors according to the observation of field survey.

Introduction

Through the measurement of transmitting time and speed of wavelength, the Light Detection and Ranging (LIDAR) technique can determine the range between ground objects and sensors. With the aid of a survey and a positioning system, a LIDAR system can generate three-dimensional geo-referenced point measurements (Shan and Sampath 2005, 217). Compared with the traditional surveying and mapping systems and the photogrammetric systems, clients widely accept LIDAR as a fast and economical resource for measuring large area and high-resolution terrain surface. Despite the advantage of LIDAR data, it can be problematic because of non-selective reflectance, which includes both the reflectance from bare-ground and non-ground objects such as trees, buildings, vehicles, electricity wires, and cars. Since DTM models come from the interpolation of bare ground points, these non-ground points should be labeled and removed from the point measurements (Zhang et al. 2003, 872; Shan and Sampath 2005, 217; Zhang and Whitman 2005, 313; Vosselman 2000, 935).

There are many filters that have been developed to remove non-ground points based on different characteristics of ground points. The most frequently used characteristics are elevation difference and slope change. Assuming that there is no sharp change in natural terrain, the elevation and slope in the bare ground area should change gradually. Whereas on the boundary of ground and non-ground areas, the elevation difference and slope between the ground and its neighboring non-ground points should be much larger than those between the ground and its neighboring ground points.

Whitman et al. develop an elevation threshold with an expanding window filter based on the elevation difference between the points and their neighbors (Zhang and Whitman 2005). Vosselmann (2000) presents a slope-based filter based on erosion morphology. Zhang and Whitman (2005) test a maximum local slope filter similar with that of Vosselmann.

Instead of only considering elevation or slope factors, other filters combine these two characteristics to remove non-ground points. Shan and Sampath (2005) develop a one-dimensional and bi-directional filter based on the elevation difference and slope between the two neighboring points along the scanning directions. Compared to a two-point neighborhood, morphology filters define a neighborhood window, which can be either one-dimensional or two-dimensional such as a rectangular, circular or user-defined neighborhood. Zhang et al. (2003, 873-4) cite that Kilian and others propose a morphology filter based on an opening process. But the selection of the window size and the distribution of non-ground points are critical to its performance, and it is restricted in a complicated area. To solve this problem, Kilian et al. introduce an iterative morphology method with different window sizes, and assign a weight to each point according to the window size. Based on their research, Zhang et al. develop a progressive morphological filter to label ground points by gradually increasing the size of the windows.

Some filters introduce new techniques from other disciplines or combine LIDAR data with new resources. Okagawa (2001) discriminates ground and non-ground points through a cluster analysis. Haugerud and Harding (2001) propose a filter based on the local curvature to remove trees in a forest area. Passini and Jacobsen (2002) present a filter based on the linear prediction method. Lohmann et al. (2000) compare the linear prediction algorithm with a dual-rank morphology filter proposed by Eckstein and Kunkelt, which introduce the concept of sorting the elevation of the points in neighborhood. Elmqvist et al. (2001, 2002) extract ground points based on the contour and shape model. Zhang and Whitman (2005, 313) cite that Axelsson developed an adaptive TIN filter to identify ground points. Instead of separating the processes of removing non-ground points and interpolation, an iterative robust interpolation method removes the ground points during the process of comparing the DTMs created in different resolutions in terms of point density (Schickler and Thorpe 2001; Kraus and Pfeifer 2001; Kraus and Rieger 1999).

This paper presents a new slope and elevation based filter based on the one-dimensional and bi-directional filter proposed by Shan et al. (2003). This paper first uses a quantitative error analysis to compare the performance of the both filters. Using a different method to generate the ground truth images, this paper presents an error distribution analysis that few literatures discuss. Then, this paper experiments and compares the two filters in a larger urban area on a small hill to test the reliability and flexibility of the filters to big and complex areas.

An improved slope and elevation based filter

Definition of ground points

To validate ground filtering, ground points should be mathematically defined. Based on the criteria the method uses, Shan and Sampath (2005, 219) mathematically define the ground and non-ground point as:

$$\text{Image}[i,j]\begin{cases}\text{If } (Sv>St \text{ and } Zi>Zt) \text{ non ground point}\\ \text{Otherwise ground point}\end{cases} \tag{1}$$

Image[i,j] refers to any point in the image, in which i and j refer to the location. Sv is the slope between the two neighbor points along scanning directions. St is the threshold of maximum terrain slope. Zi is the elevation difference between the scanning point and the searched nearest ground point. Zt is the predefined threshold of maximum elevation difference. Given any point in the image, if the slope is greater than the maximum slope and the elevation difference between the point and the nearest ground point is greater than maximum elevation difference, the point is non-ground point. Otherwise, it is a ground point.

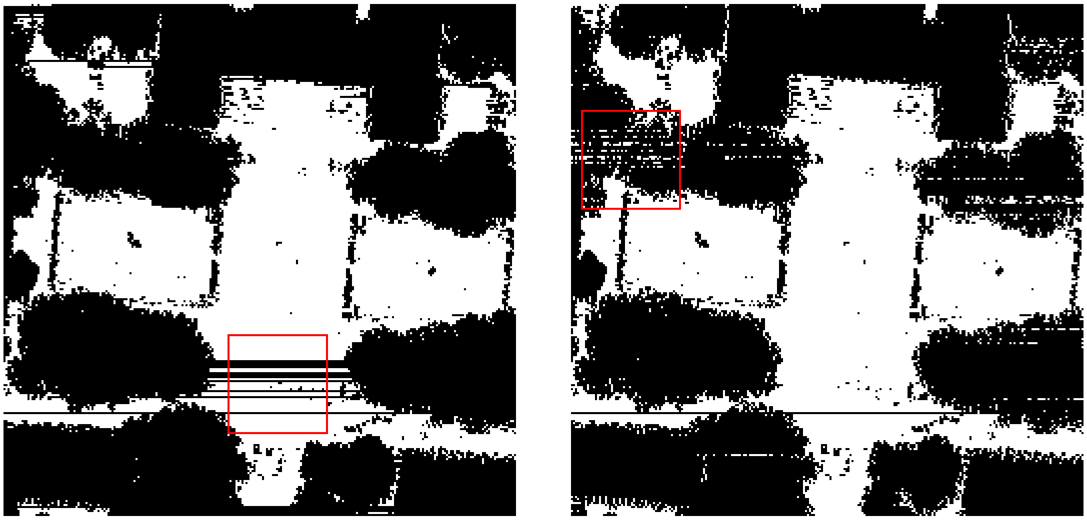
One-dimensional and bi-directional labeling filter (OBL)

Shan and Sampath (2005) present a one dimensional and bi-directional labeling method to label ground points based on maximum slope and elevation. In this method, each point has two labels: ground point or non-ground point. The method first scans the image row by row from left to right. To make sure that it could always find the nearest ground point, it assumes the first scanning point of the row as ground. Then, the following points are labeled as ground until slope is greater than the maximum threshold St. If the label of the former point is non-ground, then the method labels the following points as non-ground until the slope is less than 0. If the label of the former point is non-ground and the slope is less than 0, the method searches the labeling result of the row to search for the nearest ground point, and calculates the elevation difference between the scanning point and the nearest point. If the elevation difference is greater than the maximum threshold Zt, then it labels the point as non-ground. Otherwise, it labels the point as ground. It repeats the labeling process for each row of the image until it labels each point of the image.

Because the method always assumes the first scanning point as ground, if the row starts with non-ground point, such as trees and buildings, it will label some non-ground points as ground points. In order to solve this problem, the method repeats the labeling algorithm from the other direction, namely from right to left. Then, this method intersects the labeling ground results of both directions as final ground point results, which means that for each point, it is a ground point only when it is both labeled as ground in each directional labeling result. Instead of horizontal scanning, users can also choose vertical scanning.

Instead of considering only maximum elevation or slope criterion, this algorithm combines elevation, slope, and the nearest ground point. The algorithm is easy to understand and repeat, and is less computationally time-consuming. It also has some limitations.

This paper observes three limitations based on the test results. First, by always assuming the first scanning point as ground, no matter whether it is a ground or not, different rows of labeling may make different assumptions. Therefore, it limits the nearest point to be a one-dimensional search. Second, because of the first limitation, if the row comes across a big non-ground area and the terrain deference is greater than the threshold Zt, then it will label the ground point as non-ground. This problem creates unexpected stripes in the ground area, which should be ground but labeled as non-ground. Increasing the threshold Zt may reduce the chance of stripes, but it will also introduce errors into the result, which should be non-ground but is labeled as ground (see Figure 1.). Third, because of this assumption, the method utilizes intersection to combine the results of bi-directional labeling.



(a) (b)

Figure 1. Labeling results with the same slope thresholds and different thresholds of Zt. White is ground and black is non-ground. (a) Zt=2 m, some unexpected stripes exist in rectangle area. (b) Zt=4 m, although with fewer unexpected stripes, it introduces errors by labeling non-ground points to ground points as in rectangle area.

Therefore, the final intersection results will be the smallest collection of the ground points. Those ground points that cannot be identified in any directional labeling will remain in the final results. An obvious example is that, if there are unexpected stripes in the ground area in any directional labeling, the stripes will remain in the final ground collections.

One-dimensional scanning, two-dimensional nearest point searching and four-directional labeling filter (OTFL)

To solve the limitations above, this paper improves the method in five ways. First, there is no assumption made for the ground points. Therefore, there are no nearest ground points at the beginning of the first row. To solve this problem, it is necessary to take a ground point seed near the starting point, which is labeled before filtering. Second, instead of bi-directional labeling, users can choose to combine two, three or four directions. Usually, scanning of two directions can obtain a satisfactory result. Third, because there is no ground assumption as the original method does, this filter only labels ground points as ground points. To take advantage of multi-directional scanning, the identified ground points from the former scanning results remain in the label feature for subsequent scanning. The ground points that are not correctly identified in one direction may be improved in other directions. Therefore, the final results will be larger than the one-directional labeling result. But for the original method, since the intersection results are always the smallest collections, there is no method to reduce the errors of labeling ground as non-ground by increasing the number of scanning directions. Fourth, instead of one-dimensional searching of nearest points, this improved filter searches the nearest points in two-dimension. Therefore, the chances of finding the nearest ground points increase substantially, which make it possible to use a smaller elevation difference threshold and essentially reduce the unexpected stripes. Fifth, the filter also considers the elevation difference between the center point and its neighboring points.

One ground point seed is necessary for the first potential ground point so that the filter can always find a ground point in the labeled result if necessary. The provided ground sample should be close to the first potential ground point. There are three attributes for each point labeling result: ground, non-ground, and uncertain.

The method first compares the elevation with the neighboring points to check whether the point is non-ground point. If not, the method labels the starting points as uncertain until the slope is greater than the pre-defined maximum slope threshold. The slope is defined as the slope between the scanning point and its former scanning point. Then, if the local elevation differences do not prove the points as non-ground points, the filter will label the following points as non-ground until the slope is less than 0. A slope less than 0 means the filter is scanning downhill. If the former point is non-ground and S[i,j] is less than 0, it may be ground or lower non-ground. In this case, it searches the nearest ground point in two-dimensional labeling results and calculates the elevation difference between the point and the searched nearest ground point. If the elevation difference is greater than the maximum elevation threshold Zt, it is a non-ground point. Otherwise, it is a ground point. If the former point is a ground point and the scanning point is not checked as non-ground, it labels the following points as ground until the slope is greater than the maximum slope.

After scanning in one direction, the method reorganizes the label feature into only two statuses, ground and uncertain. The filter then iterates the labeling process in other directions.

Performance comparison of filters

To compare the performance of these two filters, this paper tests the filters both on a small and a large area. For the smaller area, this paper applies a quantitative error analysis to assess and compare the quality of the results and analyze the characteristics of the error distribution. Next, the two filters are examined in a larger complex area to test the reliability and flexibility of the filters to different types of ground surface.

Study site and preprocess

Two study sites are located at the University of Texas in Austin. The smaller site covers 16,384 square meters area, and the observed features include the ground, trees, flagpoles, and buildings. The density of raw LIDAR data is 3 points per square meter, and only first return is used to identify ground points. For preprocess, it first filters the noise in the raw data, usually expressed as extremely high or low values. Therefore, LIDAR points with values fall out of certain range are removed from the dataset. Then, an interpolation method estimates the surface with a cell size of 0.5 meters.

The second site is also the first-return, which covers 0.51 km^2 with a cell size of 1 meter. The site is covered with high density of non-ground objects, such as the ground, shrubs, trees, buildings, bridges, vehicles, flagpoles, short walls, and fences. The largest building is 114-meters wide and

194-meters long. The site is located on a small mountain area, with elevation decreases from left to right.

Table 1. Parameter of the study site

Study site	Image size	Cell size	Area	Maximum slope	Time
University of Texas, Austin	256*256	0.5 m	0.016 km^2	< 30 °	2000
University of Texas, Austin	730*695	1 m	0.51 km^2	< 30 °	2000

This paper presents a way to generate the ground truth images. As the results of these filters are points labeled as ground and non-ground, this paper endeavors to classify the smaller image into ground and non-ground based on field survey on May 7, 2005, and then compares with the filtering results. There are two steps to generating the ground truth image. First, based on the observation of the elevation histogram, a segmentation method is used to devide the ground into several parcels. Then, points that are 0.5 meters higher than the surrounding neighbors are manually edited as non-ground based on the field survey. Therefore, shrubs, trees, and short walls are carefully sampled as non-ground. The final results are processed into two classes, ground and non-ground. The accuracy reports include overall accuracy and Kappa value. Although a lit bit time-consuming to edit the ground truth samples, it is a valuable tool and operational in smaller areas.

Results and discussions

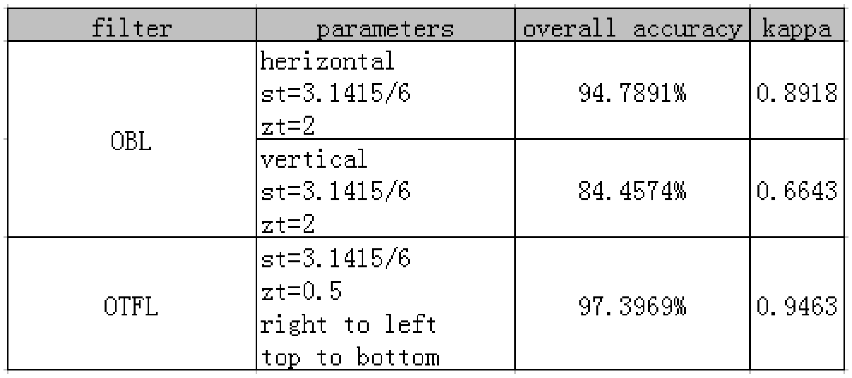
Figure 2 is the optimum result of the two filters in the smaller area, and Table 2 is their parameters and accuracy assessment. The optimum results are defined as those with the best visual comparison with the least obvious error and highest overall accuracy and Kappa value.

Figure 2 list the optimum result in the smaller area. (a) is the first return of LIDAR data. (b) is the ground truth data edited according to field survey. (c) is the optimum result of the OBL filter in horizontal directions. (d) is the optimum result for OTFL filter scanned from left to right and from top to bottom.

According to a visual comparison, the OTFL filter preserves a better shape of the ground objects. It is also sensitive to small sharp change areas, such as shrubs, and short walls, which are difficult for most filters. No obvious errors in the final results can be easily identified with the bare-eye. There are some stripes in the ground area in the OBL filter, which are the errors that should be classified as ground but are labeled as non-ground. This occurs because when the filter scans through a larger object and the elevation difference between the two ends are bigger than the pre-defined threshold, the filter labels those points as non-ground.

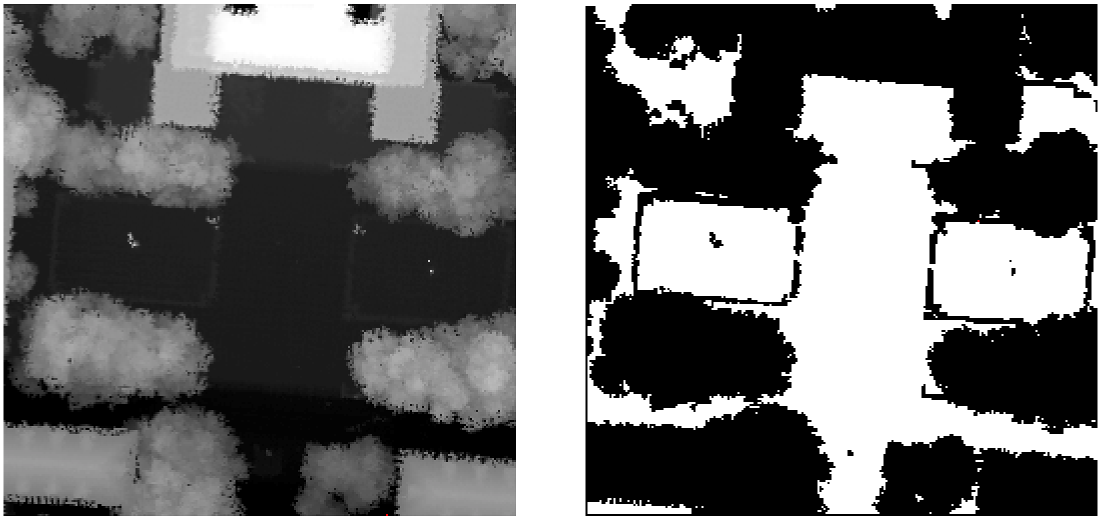
To compare the performance more clearly, Table 2 presents the parameters for those optimum results. According to the table, the OTFL filter provides a better result, improving the performance from 94.7891% to 97.3969%. For an image with a 0.5 meters cellsize, the OTFL filter can utilize an elevation threshold of 0.5 meters, which is more reasonable than the threshold of 2 meters of the OBL filter. The selection of scanning directions is critical to the OBL filter. To better compare the performance, this paper also test the performance of the OBL filter in vertical direction. The overall accuracy is 84.4574%, which is much lower than in the horizontal directions. This is because the elevations in the image increase from bottom to top, and the OBL filter generates more stripes when scanning from bottom to top. As a result, the errors will remain in the final results because of the intersection process. This means that the selection of scanning directions is critical to the performance, and the performance is vulnerable to the spatial distribution of the objects.

Table 2. Parameters and accuracy comparison for optimum performances



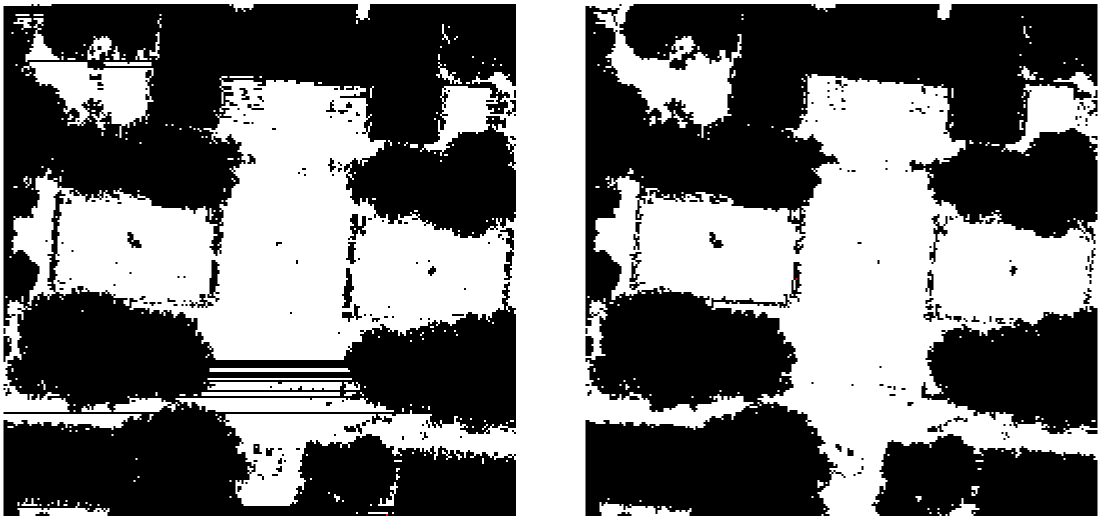
filter	parameters	overall accuracy	kappa
OBL	herizontal st=3.1415/6 zt=2	94.7891%	0.8918
	vertical st=3.1415/6 zt=2	84.4574%	0.6643
OTFL	st=3.1415/6 zt=0.5 right to left top to bottom	97.3969%	0.9463

There are two basic errors: the commission error and the omission error (Zhang and Whitman 2005, 315). The former are the errors that classify non-ground as ground, which should be avoided as much as possible. The latter are the errors that classify ground as non-ground. Figure 3 compares the error distribution of the optimum results for both filters, which show that most commission and omission errors are distributed on the boundaries of the objects, which are usually the sharp changes of elevation. This information is important, because it means the accuracy in boundary areas is critical to the actual accuracy, which makes it a big challenge to the selection of the location of ground truth points. The OBL filter will generate some obvious errors within the areas of ground, which are usually continuous lines as shown in (b) of Figure 3. The error statistics in Table 3 show that the OTFL filter generates both fewer commission and omission errors.



(a) Original LIDAR data (first return)

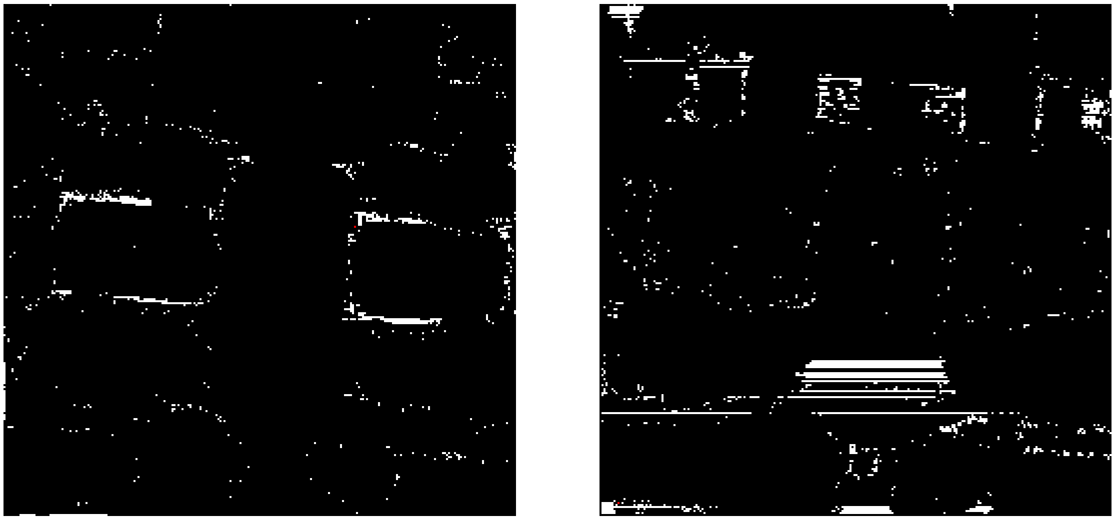
(b) ground truth image



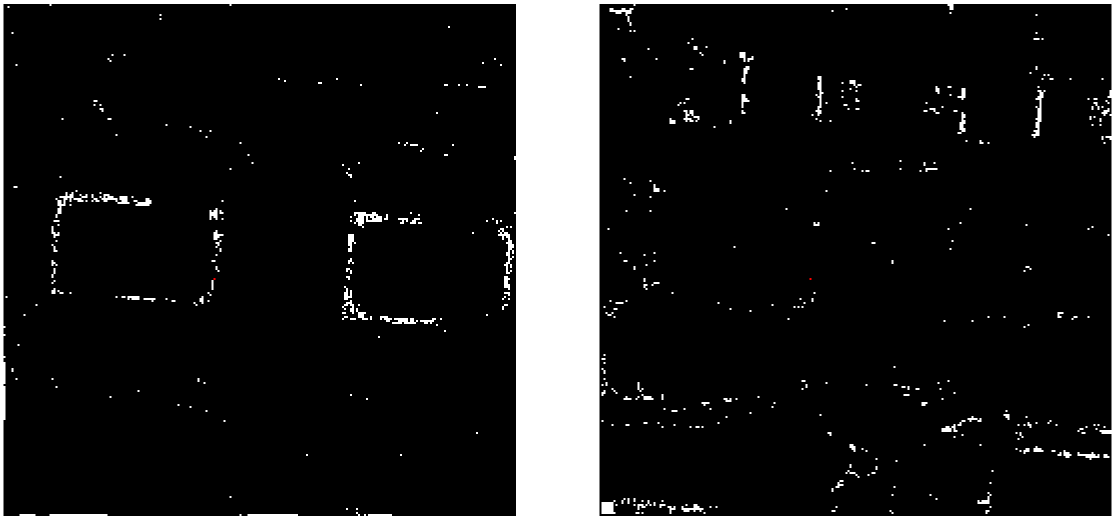
(c) Result of OBL filter

(d) Result of OTFL

Figure 2. Performance comparison in the smaller area. In (b), (c), and (d), the white represents the filtered ground points, and the black represents non-ground points. (a) unfiltered first return of the study site, (b) manually edited ground truth image, (c) result of original OBL filter, and (d) result of the improved filter, OTFL.



(a) OBL-non-ground error (b) OBL-ground error



(c) OTFL-non-ground error (d) OTFL-ground error

Figure 3. Comparison of error distributions

Table 3. The table of error statistics

class		ground truth		
		commission (percent)	omission (percent)	total pixel
OBL (Horizontal)	non-ground	6.03	2.65	39774
	ground	3.94	8.84	25762
OBL (Vertical)	non-ground	19.92	2.2	46891
	ground	4.52	34.42	18645
OTFL	non-ground	2.4	2.03	36839
	ground	2.89	3.41	28697
total pixel		38391	27145	65536

Table 4. Test of the dependency on the selection of directions

filter	parameters	overall accuracy	kappa
OTFL	st=3.1415/6 zt=0.5 left to right top to bottom	97.3160%	0.9446
	st=3.1415/6 zt=0.5 left to right right to left	97.2519%	0.9433
	st=3.1415/6 zt=0.5 left to right bottom to top	97.3419%	0.9452
	st=3.1415/6 zt=0.5 right to left top to bottom	97.3969%	0.9463
	st=3.1415/6 zt=0.5 right to left bottom to top	97.3404%	0.9451
	st=3.1415/6 zt=0.5 herizontal top to bottom	97.3969%	0.9463
	st=3.1415/6 zt=0.5 herizontal vertical	97.3373%	0.9451

To test whether the OTFL filter is vulnerable to the selection of directions, this paper illustrates different pairs of combinations as shown in Table 4. The overall accuracies are higher than 97.2%, and the lowest is 97.2591%, which is also highly accurate. The results show that the selection of directions has little influence on the final results.

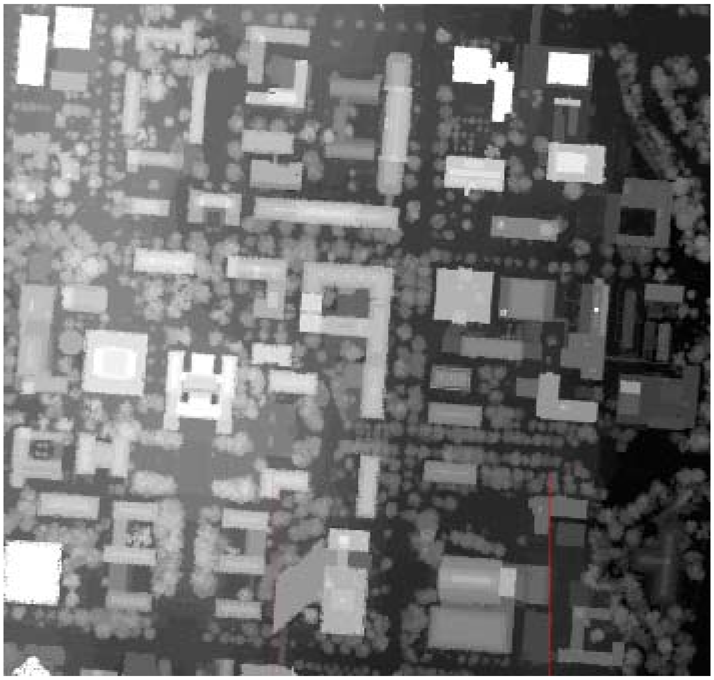
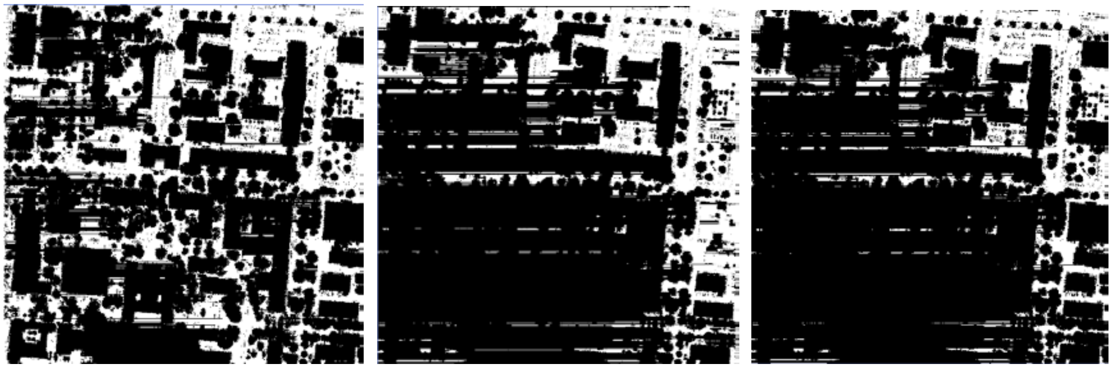


Figure 4. First return of the larger study site

To test the flexibility and reliability of the filters for larger and complex areas, this paper applied the two filters in a larger area. Figure 4 is the first return of the study site. The largest building within the area is 114-meters wide and 194-meters long.

Figure 5 is the result of the OBL filter. The maximum slope threshold is 0.52 degrees, and the maximum elevation threshold is 2 meters. Because the elevations increase from right to left, when the filter scans from right to left and the elevation differences between the two ends of the non-ground objects are larger then the maximum elevation threshold, the filter will label those points as non-ground. In Figure 5 (b), a large mount of ground points is labeled as non-ground because of the accumulated errors. Those errors remain in the final result of (c) because of intersection process of (a) and (b). The result shows that when applied to a complex area with a greater slope change, the filter fails to extract the ground points, as the filter is vulnerable to slope change, particularly when it scans along an ascending direction.

Figure 6 is the result of the OTFL filter scanned from left to right and from top to bottom. The maximum slope threshold is 0.52 degree, and the maximum elevation threshold is 0.5 meters. Although applied to a much larger and complex area, the filter can still use a small elevation threshold compared to the OBL filter. No obvious error exists according to the observation of the field survey. The result shows that the filter is sensitive to small sharp changes, which are difficult for most other filters to detect. Even litter shrubs, short walls, and vehicles are detected in the final result.



(a) Left to right (b) Right to left (c) Intersection

Figure 5. The result of OBL on the second study site

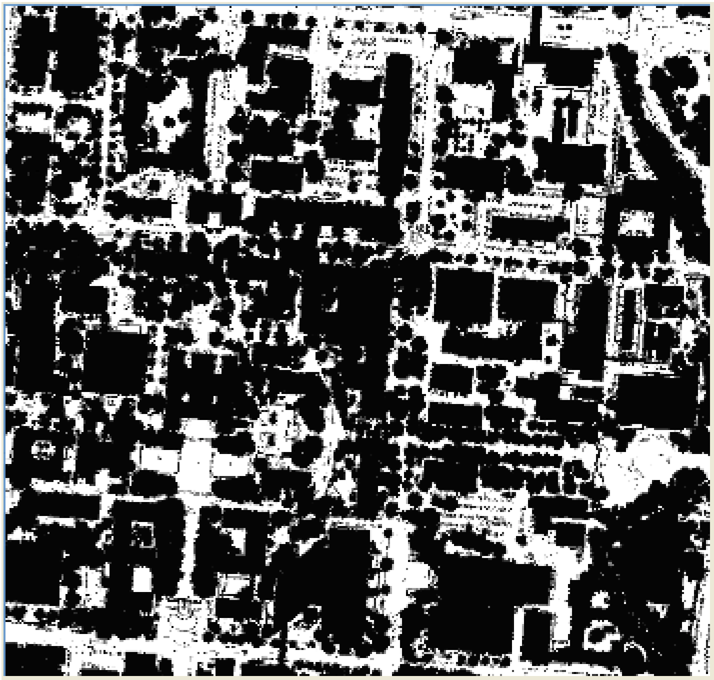


Figure 6. The result of OTFL

Advantage and disadvantage

Compared with the OBL filter and other filters, the OTFL filter presents the following advantages:

1. The filter is not vulnerable to slope change. When applied to a hill area, the OBL filter usually fails to extract the ground points from the LIDAR images. However, the OTFL filter has a greater chance in detecting closer ground points, which makes it applicable to areas with a complex slope change.
2. Considering the local elevation, the OTFL filter can use a smaller and reasonable maximum elevation threshold, even when applied to a large and complex area.
3. Because of the first two advantages, the OTFL filter can be applied to larger areas, which

usually have more complex ground covering and greater slope change.

4. The results show that the OTFL filter is sensitive to small sharp change areas, such as shrubs and short walls, which are difficult for most other filters to detect. This filter can also detect small sharp change non-ground points that are even hard to detect with bare-eyes, such as arow parked vehicles.
5. The size of the objects will not influence the performance of the OTFL filter. Many filters that are based on a process of a pre-defined window, such as some morphology filters, fail to identify the non-ground objects which are larger or smaller than the window size.
6. The results show that the OTFL filter has a strong ability to preserve the shape of the objects.
7. There is more freedom in the scanning direction selection. Users can choose any two, three, or four scanning directions, and the experiments show that there is little difference in the combinations, which means the OTFL filter is not vulnerable to the selection of the scanning directions.
8. Few adjustable parameters make the filter easy to test for the optimum results. Some filters have more than 3 adjustable parameters. This means there are many combinations of the parameters to test for optimum results. Given a particular image, the OTFL filter only needs to adjust the maximum slope and elevation thresholds, which is fast and convenient in practice.
9. Because the pre-non-ground check prevents errors from the beginning, it also reduces the

accumulated errors in the final results.

10. The quantitative error analysis proves that the OTFL generates fewer commission and omission errors.

The disadvantage of the OTFL filter is that it is necessary to provide a ground seed that is close to the first scanning point, which is easy to obtain from the images.

Conclusions

For a smaller and low relief urban dataset, both the OBL filter and the OTFL filter work well. The OTFL filter improves the accuracy from 94.7891% to 97.3969%, and the Kappa values increase from 0.8918 to 0.9463. Compared to the elevation threshold of 2 meters of the OBL filter, the OTFL filter can apply a 0.5-meter threshold, which is smaller and more suitable to a cell size of 0.5 meters.

The experiments prove that the original OBL filter is vulnerable to the selection of scanning directions and the distribution of the objects, which is conquered by the OTFL filter. The quantitative error analysis proves that the OTFL filter also generates a higher accuracy with both fewer commission and omission errors.

The OTFL filter presents a better ability to preserve the shape and boundary of objects. When applied to a larger and more complex area, the OBL filter fails to identify the ground points from the LIDAR data. However, the OTFL filter generates good results with no obvious errors according to the observation of the field survey. Because the filter considers the local elevation difference during scanning, a small elevation threshold is still applicable to a larger area,

Acknowledgments

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References Cited

Elmqvist, M., 2002. Ground surface estimation from airborne laser scanner data using active shape models, *ISPRS Commission III Symposium 2002, Photogrammetric and Computer Vision*, 9-13 September 2002, Graz, Austria, pp. 114-118.

Elmqvist,M., E. Jungert, F. Lantz, A. Persson, and U. Soderman, 2001. Terrain modelling and analysis using laser scanner data, *International Achives of Photogrammetry and Remote Sensing*, XXXIV, part 3/W4: 211-218.

Haugerud,R. A., and D.J. Harding, 2001. Some algorithms for virtual deforestation (VDF) of LIDAR topographic survey data, *International Archieves of Photogrammetry and Remote Sensing*, XXXIV, part 3/W4: 219-226.

Hill, J.M., L.A. Graham, R.J. Henry, D.M. Cotter, A. Ping, and P. Young, 2000. Wide-area topographic mapping and applications using airborne light detection and ranging (LIDAR) technology, *Photogrammetric Engineering & Remote Sensing*, 66(8): 908-x.

Lohmann, P., A. Koch, and M. Schaeffer, 2000. Approaches to the filtering of laser scanner data, *International Archives of Photogramm. Remote Sensing*, 33(B3): 540-547.

Okagawa, M., 2001. Algorithm of multiple filter to extract DSM from LIDAR data, *2001 ESRI International User Conference, ESRI*, 23-25 July 2001, San Diego, California.

Passini, R., and K. Jacobsen, 2002. Filtering of digital elevation models, *Proceedings of the ASPRS 2002 Annual Convention*, 19-26 April 2002, Washington DC (American Society for Photogrammetry and Remote Sensing, Bethesda, Maryland), unpaginated CD-ROM.

Schickler, W., and A. Thorpe, 2001. Surface estimation based on LIDAR, *Preceedings of ASPRS Annual Conference*, 23-27 April 2001, St. Louis, Missouri, USA, unpaginated CD-ROM.

Shan, J., and A. Sampath, 2005. Urban DEM generation from raw LIDAR data: A labeling algorithm and its performance, *Photogrammetric Engineering & Remote Sensing,* 71(2): 217-226.

Vosselmann, G., 2000. Slope based filtering of Laser altimetry data, *International Archives of Photogrammetry and Remote Sensing* XXXIII Part B3, Amsterdam 2000: 935-942.

Zhang, K., and D. Whitman, 2005. Comparison of three algorithms for filtering airborne LIDAR data. *Photogrammetric Engineering & Remote Sensing*, 71(3): 313-324.

Zhang, K., S. Chen, D. Whitman, M. Shyu, J. Yan, and C. Zhang, 2003. A progressive morphological filter for removing nonground measurements from airborne LIDAR data. *IEEE Transactions on Geoscience and Remote Sensing*, 41(4): 872-882.