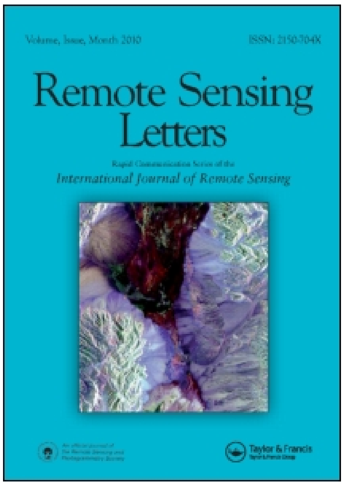

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Sensitivity of LiDAR-derived three-dimensional shape signatures for individual tree crowns: a simulation study

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Sensitivity of LiDAR-derived three-dimensional shape signatures for individual tree crowns: a simulation study

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Following previous research that demonstrates the effectiveness of three-dimensional (3D) shape signatures for characterizing individual tree crowns derived from Light Detection and Ranging (LiDAR) data, this letter presents a simulation study on the sensitivity of 3D shape signatures. Based on the observation of LiDAR point clouds for tree crowns, a mathematical model is designed to generate simulation data. Factors affecting LiDAR-derived 3D shape signatures of individual tree crowns are then tested, including the number of points, the size and location of sampling circles and the influence of neighbouring crowns. The results suggest that it is possible to obtain 3D shape signatures of individual crowns based on automated treetop detection, and that a combination of multiple sample circles may provide more reliable results than single sample circles in characterizing 3D crown shapes.

1. Introduction

Canopy structure information, including the sizes, shapes and relative placement of the tree crowns in forest stands, is useful for studying all aspects of forest ecology (Purves *et al*. 2007). In previous research (Dong 2009), the effectiveness of 3D shape signatures in characterizing individual tree crowns was demonstrated using computer simulations and manually selected samples of Light Detection and Ranging (LiDAR) data for oak and Douglas fir crowns in both vector and raster formats. The basic idea behind 3D shape signatures is to transform an arbitrary 3D object into a parameterized function that can easily be compared with other objects (Osada *et al*. 2002). The shape function used in Dong (2009) measures the 3D Euclidean distance between two random points selected from LiDAR point clouds or a digital surface model of a tree crown. After a certain number of iterations (e.g., 10,000) of the distance calculation, 50 histogram bins are used to summarize the frequency distribution of the distances between point-pairs, which can be further converted to a probability distribution for comparison between different 3D crown shapes.

The following questions need to be answered before 3D shape signatures can be incorporated into automated information extraction procedures for LiDAR data: (1) What is the minimum number of LiDAR points that can be used to characterize a tree crown using 3D shape signatures? (2) Can 3D shape signatures be obtained from a sample area on the crown rather than the whole crown? (3) To what extent do LiDAR points from mistakenly included neighbouring tree crowns affect 3D shape signatures

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of the target crown? The objective of this research is to address these questions using computer modelling and simulation. Software tools were developed in ArcGIS 9.3 using ESRI's ArcObjects 9.3 and Microsoft Visual Basic for Applications (VBA).

2. Methodology

2.1 *Generation of LiDAR point clouds for tree crowns*

In the previous study (Dong 2009), random points with random elevation variations near the surfaces of three simple geometric models (cone, hemisphere and half-ellipsoid) were generated to simulate LiDAR points. Further observation of LiDAR point clouds for individual conifer and deciduous tree crowns in the Soquel State Demonstration Forest near Santa Cruz, California, indicates that majority of the LiDAR points were distributed in a layer near the crown surface. Interestingly, the layer seems to be confined between a simple geometric model (such as a half-ellipsoid) and a reduced-sized model of the same shape in many cases. Figure 1(*a*) shows LiDAR points of a real conifer tree crown in the Soquel State Demonstration Forest selected from the data set collected by the GeoEarthScope Northern California LiDAR project (Prentice *et al*. 2009). The red points in figure 1(*a*) are selected LiDAR points from the xz plane to show the point distribution in a profile. The outer surface $f_2(x, y)$ of the points is a half-ellipsoid with both major axis and minor axis, r, whereas the inner surface $f_1(x, y)$ is a half-ellipsoid with both major axis and minor axis, d. Theoretically, d can change in the range of $0 < d < r$, depending on the tree species and season (leaf-on or leaf-off). For simplicity, $d = r/2$ is used to construct the model for generating simulation data (figure 1(*b*)). Similar diagrams can be drawn for conic and hemispheric models.

Based on the model in figure 1, random points can be generated in a circle with radius r in the xy plane, and with height values, z, using the following equations:

$$z(x,y) = f_2(x,y)t \quad \left(\left(\frac{r}{2}\right)^2 \leq x^2 + y^2 \leq r^2\right) \tag{1}$$

$$z(x,y) = f_1(x,y) + (f_2(x,y) - f_1(x,y))t \quad \left(x^2 + y^2 < \left(\frac{r}{2}\right)^2\right) \tag{2}$$

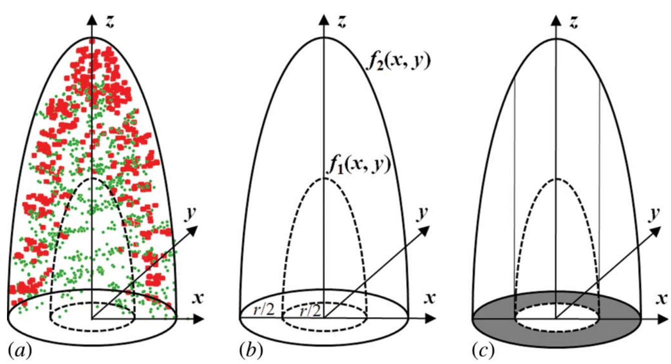

Figure 1. (*a*) Real LiDAR points selected from a crown profile; (*b*) the outer surface $f_2(x, y)$ and inner surface $f_1(x, y)$ of the geometric model; (*c*) the outer zone (shaded) and inner zone for generating random points.

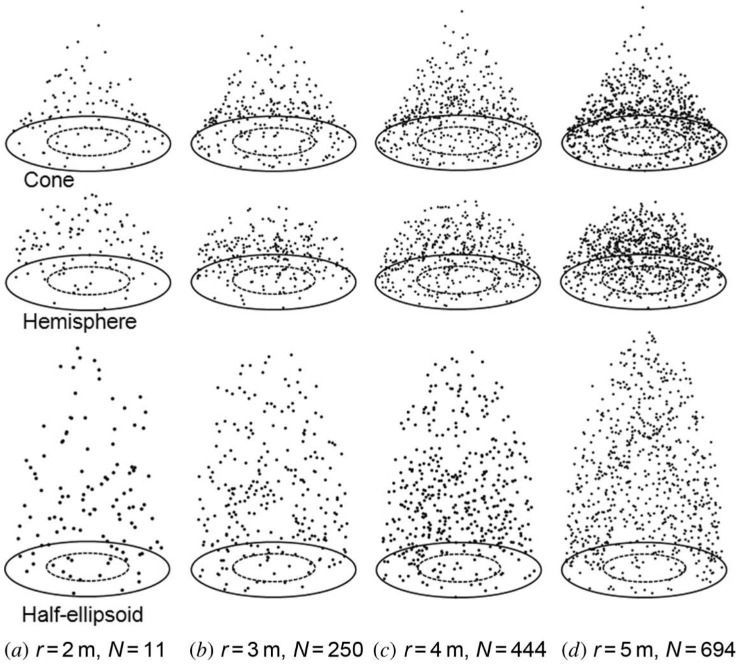

Figure 2. Perspective view of simulated tree crowns with different base radius and number of points.

where t is a random number between 0 and 1. Equation (1) is for points above the shaded ring in figure 1(*c*), and equation (2) is for points above $f_1(x, y)$ and below $f_2(x, y)$. The surfaces can be defined by geometric models such as a cone, hemisphere and half-ellipsoid (Dong 2009). Figure 2 shows simulated tree crowns for this study (height to radius ratio of 1.732:1 for cone and 3:1 for half-ellipsoid), with different radius r. The total number of points, N, for each crown varies such that the average density is 8.8 laser points per square metre, similar to the laser point density in the Soquel State Demonstration Forest data set collected by the GeoEarthScope Northern California LiDAR project (Prentice *et al*. 2009).

2.2 *Measurement of similarity between 3D shape signatures*

Calculation of 3D shape signatures for each simulated crown was repeated five times, and the average of the five signature curves for each crown was also calculated. Correlation coefficients between averaged curves were used as a quantitative measure of similarity between 3D shape signatures.

3. Results and discussion

3.1 *Minimum number of points for 3D shape signature calculation*

Figure 3 shows the 3D shape signatures of the tree crowns in figure 2. As a measure of similarity between 3D shape signatures, correlation coefficients were calculated and listed in table 1. Results from different runs of the same crown model show high correlation coefficients of over 0.99 (not shown in table 1), whereas lower correlation

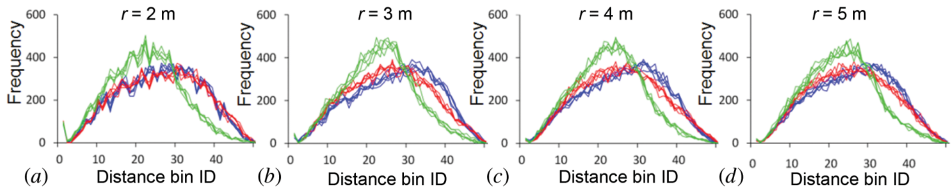

Figure 3. 3D shape signatures of the tree crowns in figure 2 (blue – cone, red – hemisphere, green – half-ellipsoid).

Table 1. Correlation coefficients between 3D shape signatures obtained from crowns with different base radius (r).

	$r = 2$ m			$r = 3$ m			$r = 4$ m			$r = 5$ m		
	Cone	Sphr	Elps	Cone	Sphr	Elps	Cone	Sphr	Elps	Cone	Sphr	Elps
Cone	1	0.95	0.75	1	0.94	0.73	1	0.95	0.76	1	0.96	0.83
Sphr	0.95	1	0.77	0.94	1	0.87	0.95	1	0.89	0.96	1	0.92
Elps	0.75	0.77	1	0.73	0.87	1	0.76	0.89	1	0.83	0.92	1

Sphr – semisphere; Elps – half-ellipsoid.

coefficients were obtained when comparing two different 3D crown shape signatures. When the number of points is 250 or more (i.e. $r \geq 3$ m in figure 3), the 3D shape signatures are stable and can potentially be used for characterization of individual 3D crown shapes. An alternative interpretation of figure 3 is that tree crowns with the same shape but different sizes will have the same 3D shape signatures, as long as enough LiDAR points (at least 250 in this case) are collected for each crown. This property arises because the distance bin ID parameter is scaled by the modelled tree size.

3.2 *Size and location of sample circles for 3D shape signature calculation*

Figure 4 shows a crown with radius $r = 5$ m (also see figure 2(d)), and a sampling scheme in which sample circles with radius s are around the crown centre (figure 4(a)), or centred at a point 1 m or 2 m away from the crown centre (figures 4(b) and (c)).

Figure 5 shows the 3D shape signatures of a crown (with radius $r = 5$ m) obtained from the sample circles with different sizes and locations shown in figure 4. When the radius of sample circle $s = 1$ m, only 50–60 points were selected, and the 3D shape signatures calculated from these points were not stable (not shown in figure 5). Correlation coefficients between the 3D shape signatures are listed in tables 2–4.

The following general results can be obtained from figure 5 and tables 2–4: (1) 3D shape signatures obtained from sample circles of different sizes are different: in other words, 3D shape signatures from a sample circle may not match the 3D shape signatures of the whole crown exactly, unless the sample circle is very close to the crown boundary; (2) 3D shape signatures calculated from different sizes of sample circles may show different degrees of separability between crown shapes (signatures obtained with $s = 2$ m and $s = 3$ m are better than those with $s = 4$ m in this case); (3) slight deviation (less than 20% of crown width) of the centre of sample circles from

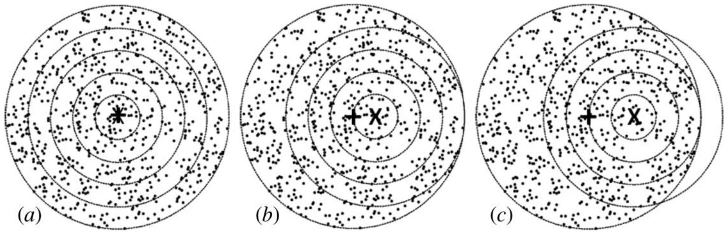

Figure 4. Size and location of sample circles ($s = 1$ m, 2 m, 3 m and 4 m) for a crown ($r = 5$ m). + is the crown centre, and x is the centre for the sample circles. (*a*) No offset; (*b*) offset = 1 m; (*c*) offset = 2 m.

the crown centre does not change the 3D shape signatures notably, as shown in figure 4(*b*) and the first two rows in figure 5; and (4) when the deviation of the centre of sample circles from the crown centre is between 20 and 40% of crown width, changes in 3D shape signature values may be observed, but the crown shapes may still be separable.

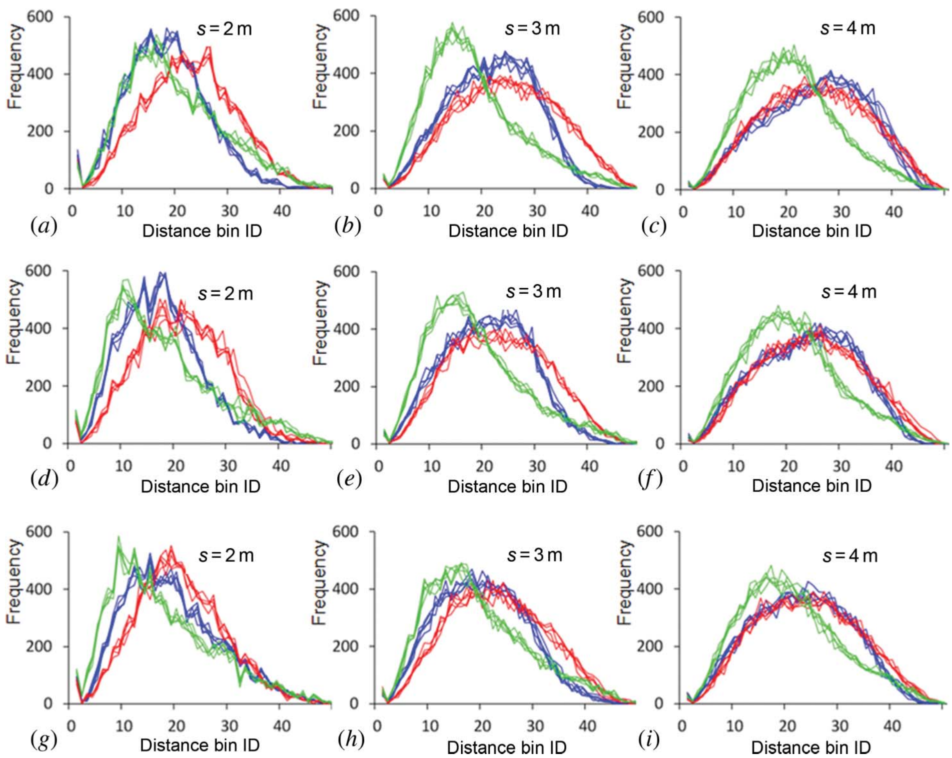

Figure 5. 3D shape signatures of a crown ($r = 5$ m) obtained from sample circles with different sizes (radius *s*) and locations. First row: results from sample circles around the crown centre; second row: results from sample circles centred at a point 1 m away from the crown centre; third row: results from sample circles centred at a point 2 m away from the crown centre (blue – cone, red – hemisphere, green – half-ellipsoid).

Table 2. Correlation coefficients between 3D shape signatures obtained from sample circles (with radius s) centred at the crown centre.

	$s = 2$ m			$s = 3$ m			$s = 4$ m		
	Cone	Sphr	Elps	Cone	Sphr	Elps	Cone	Sphr	Elps
Cone	1	0.79	0.96	1	0.93	0.67	1	0.97	0.69
Sphr	0.79	1	0.77	0.93	1	0.57	0.97	1	0.78
Elps	0.96	0.77	1	0.67	0.57	1	0.69	0.78	1

Sphr – semisphere; Elps – half-ellipsoid.

Table 3. Correlation coefficients between 3D shape signatures obtained from sample circles (with radius s) centred at a point 1 m away from the crown centre.

	$s = 2$ m			$s = 3$ m			$s = 4$ m		
	Cone	Sphr	Elps	Cone	Sphr	Elps	Cone	Sphr	Elps
Cone	1	0.77	0.90	1	0.93	0.81	1	0.97	0.82
Sphr	0.77	1	0.59	0.93	1	0.71	0.97	1	0.86
Elps	0.90	0.59	1	0.81	0.71	1	0.82	0.86	1

Sphr – semisphere; Elps – half-ellipsoid.

Table 4. Correlation coefficients between 3D shape signatures obtained from sample circles (with radius s) centred at a point 2 m away from the crown centre.

	$s = 2$ m			$s = 3$ m			$s = 4$ m		
	Cone	Sphr	Elps	Cone	Sphr	Elps	Cone	Sphr	Elps
Cone	1	0.91	0.90	1	0.90	0.90	1	0.98	0.89
Sphr	0.91	1	0.68	0.90	1	0.73	0.98	1	0.84
Elps	0.90	0.68	1	0.90	0.73	1	0.89	0.84	1

Sphr – semisphere; Elps – half-ellipsoid.

3.3 *Influence of neighbouring crowns on 3D shape signatures*

In figure 4(c), when the sample circle with $s = 4$ m is used, the sampling area extends outside the crown area. If there are neighbouring crowns near the target crown, the effects of contamination by neighbouring crowns on 3D shape signatures should be analysed. Figure 6 shows a mosaic of three crowns similar to those generated in figure 2(d) and separated by straight boundaries. Six sample circles with radius $s = 3$–8 m are used to calculate 3D shape signatures centred over each of the three crowns, and the results are shown in figure 7 and tables 5 and 6.

As can be seen from figure 7 and tables 5 and 6, the three crowns can be well separated from one another using their 3D shape signatures when the radius of the sample circle is 3 m, because neighbouring crowns do not affect the target crown at $s = 3$ m. With an increase in s, more and more LiDAR points from neighbouring crowns are included, and the cone and hemisphere become inseparable from each

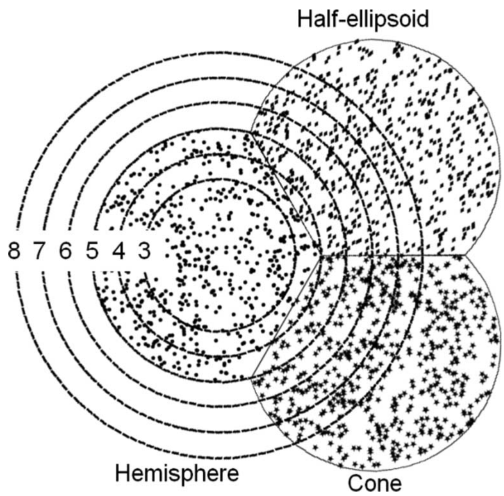

Figure 6. A mosaic of three crowns generated in figure 2(*d*) and sample circles.

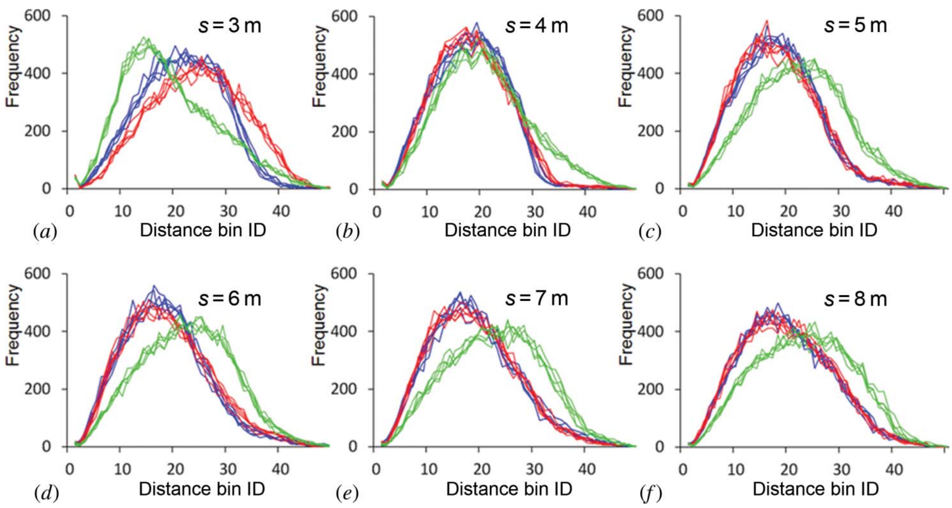

Figure 7. 3D shape signatures of the three crowns in figure 6 obtained from different sizes of sample circles (blue – cone, red – hemisphere, green – half-ellipsoid).

Table 5. Correlation coefficients between 3D shape signatures obtained from sample circles (with radius $s = 3$ m, 4 m and 5 m) for the crown mosaic in figure 6.

	$s = 3$ m			$s = 4$ m			$s = 5$ m		
	Cone	Sphr	Elps	Cone	Sphr	Elps	Cone	Sphr	Elps
Cone	1	0.91	0.76	1	0.98	0.90	1	0.99	0.72
Sphr	0.91	1	0.74	0.98	1	0.91	0.99	1	0.72
Elps	0.76	0.74	1	0.90	0.91	1	0.72	0.72	1

Sphr – semisphere; Elps – half-ellipsoid.

Table 6. Correlation coefficients between 3D shape signatures obtained from sample circles (with radius $s = 6$ m, 7 m and 8 m) for the crown mosaic in figure 6.

	$s = 6$ m			$s = 7$ m			$s = 8$ m		
	Cone	Sphr	Elps	Cone	Sphr	Elps	Cone	Sphr	Elps
Cone	1	0.98	0.74	1	0.99	0.73	1	0.99	0.79
Sphr	0.98	1	0.74	0.99	1	0.73	0.99	1	0.79
Elps	0.74	0.74	1	0.73	0.73	1	0.79	0.79	1

Sphr – semisphere; Elps – half-ellipsoid.

other using 3D shape signatures. The half-ellipsoid crown can still be separated from the other two crowns, because its elongated shape provides more point-pairs with longer distances compared with those point-pairs from the cone or the hemisphere.

Some additional points of discussion are presented below based on the above results:

1. Because a slight deviation (less than 20% of crown width) of the centre of sample circles from the crown centre does not affect 3D shape signatures notably, it is potentially possible to obtain 3D shape signatures of individual crowns based on automated treetop detection, even though treetops detected by finding the local maxima in a LiDAR-derived canopy height model may not match the true treetops.
2. If tree crowns in a canopy height model are segmented into polygons, inscribed circles in the polygons can be generated as sample circles for automated 3D shape signature analysis. Because segmented polygons can be very complex, some inscribed circles may not be useful for differentiating tree crowns.
3. Obtaining 3D shape signatures with different radius within the crown may provide more information on 3D crown shapes. This can be implemented by searching for LiDAR points near a treetop to derive multi-ring 3D shape signatures.

4. Conclusions

Based on the observation of LiDAR point clouds for tree crowns, a mathematical model was designed to generate simulated data for analysing sensitivity of 3D shape signatures of individual tree crowns. The influence of the number of LiDAR points, the size and location of sample circles, and the points from neighbouring crowns was tested. The simulation study indicated that a minimum number of approximately 250 LiDAR points is needed to characterize a tree crown using 3D shape signatures. The results suggest that it is potentially possible to obtain 3D shape signatures of individual crowns based on automated treetop detection, and a combination of multiple sample circles may provide more reliable results than single sample circles in characterizing 3D crown shapes. The results also show that LiDAR points from neighbouring crowns should be excluded as much as possible when calculating 3D shape signatures. However, LiDAR points from neighbouring crowns do not significantly affect separation of two strikingly different crown shapes such as an elongated ellipsoid and a cone.

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