

DEVELOPMENT OF A PROCEDURE FOR VERTICAL STRUCTURE ANALYSIS AND 3D-SINGLE TREE EXTRACTION WITHIN FORESTS BASED ON LIDAR POINT CLOUD

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ABSTRACT:

A procedure for both vertical canopy structure analysis and 3D single tree extraction based on Lidar raw point cloud is presented in this paper. The whole study area is segmented into small study cells by a raster net. For each cell, a normalized point cloud whose point heights represent the absolute heights of the ground objects is generated from the original Lidar raw point cloud. The main tree canopy layers and the height ranges of the layers are detected according to a statistical analysis of the height distribution probability of the normalized raw points. For the 3D extraction of individual trees, the normalized raw points are resampled into a local voxel space. A series of horizontal 2D projection images at different height levels are then generated respect to the voxel space. Tree crown regions are detected from the projection images. Individual trees are then extracted by means of a pre-order forest traversal process through all the tree crown regions at different height levels. Finally, 3D tree crown models of the extracted individual trees are reconstructed.

1. INTRODUCTION

The vertical structures of stands are of high interest in forest management. The knowledge on the vertical structure improves regression models for estimation of wood volume and biomass. It is also of high interest for assessment of the regeneration success and biodiversity aspects. Lidar is especially suitable to reproduce the vertical structure of forest stand due to its capability of three-dimensional measurements with high accuracy. The utilization of Lidar in forest investigation can be generally divided into canopy height distribution based and single tree detection based. Several approaches for Canopy height distribution detection have been achieved in the past few years (Naesset, 2002; Lim et al, 2003; Hogmgren and Jonsson, 2004), these researches are mostly concentrated with the forest characteristics of the top canopy layer. Concern the vertical distribution of canopy layers, researches based on large-footprint Lidar data with continuous waveform have been accomplished by Lefsky et al.(1999) and Harding et al.(2001). Andersen et al.(2003) has presented a method for estimating vertical structure of forest through a group of regression functions based on field investigations. As for single tree delineation, the majority of the existed algorithms are DSM (Digital Surface Model) based (Hyypä and Inkinen 1999; Persson et al. 2002; Koch et al. 2006). Trees are delineated according to the features of crowns on the DSM, thus the individual trees in the lower canopy layer whose crowns are covered by the top canopy layer cannot be detected. Beside the detection of individual trees, Pyysalo and Hyypä (2002) has provided a process for reconstructing tree crowns, with a pre knowledge of the location and the crown size of single tree, raw points belong to the tree are extracted, the height of the tree, the height of the crown and the average radius of the crown at different heights are derived.

In this paper, we will present a procedure for both vertical structure analysis and single tree extraction within forest area based on Lidar raw point cloud. The major task of vertical structure analysis is to detect the number of main canopy layers and the height range of each canopy layer. A more detailed study of the spatial features of canopies is performed by the single tree extraction process. Individual trees are detected not

only from the upper canopy layer but also from the lower canopy layer in between the ground and upper canopy layer. Shapes of individual tree crowns are then delineated and 3D models of tree crowns are reconstructed.

The raw point cloud is the basis of our analysis. Due to the huge amount of data, it is not possible to analyse all the raw points within a study area in one step. Therefore the study area is segmented into a raster net firstly. Each grid cell is then a study cell, which with a size of $20\text{m} \times 20\text{m} = 400\text{m}^2$ in this case. Further analyses are carried out for each study cell separately. The results of each study cell can then be assembled for the whole study area at the end.

The study area is in “Kuernacher Wald”, the size of this study area is $2.7\text{km} \times 2.8\text{km}$, the dataset being used is a first-last returned Lidar data, the density of raw point cloud is 4~7 points per m^2 .

2. VERTICAL STRUCTURE ANALYSIS

2.1 Normalized Point cloud

To get the absolute object height of the raw points, the influence of terrain must be eliminated (Figure 1. Left). A raster DTM (Digital Terrain Model) is used for the normalization of raw point heights. The DTM is generated from the raw point clouds by TreesVis, a software for LIDAR data processing developed by Department of Remote Sensing and Landscape Information Systems (FeLis) (Weinacker et al., 2004).

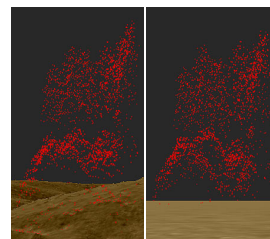


Figure 1. Comparison between original Lidar raw point cloud and normalized point cloud; Left: original Lidar raw point cloud and the DTM; Right: normalized point cloud over a zero height level surface

As been showed in Figure 1.(Left), raw points are projected above the DTM, the height difference between a raw point and its correspondent terrain is marked as the normalized height of the point. A normalized point cloud is then generated (Figure 1. Right), point heights of the normalized point cloud represent the absolute heights of the objects.

2.2 Detection of Canopy Layers

2.2.1 Height Distribution Probability of Normalized Points:

With a statistical process of the normalized points, a height distribution probability function $\phi(h)$ can be derived. According to the physical feature of Lidar data, most of the reflected points are located at canopy layers in the forest area. Therefore there should be an obvious increase of reflected points at each canopy layer. Thus, the problem of canopy layer detection is then transferred to a salient curve detection based on the height distribution probability function $\phi(h)$.

To reduce the influence of slight amplitude movements on the function, $\phi(h)$ is firstly smoothed with a gaussian function, a smoothed function $S(h)$ is generated, the second derivative $S''(h)$ is then calculated for the smoothed function $S(h)$.

As presented in figure 2., the magnitude of the second derivative is a useful criterion for salient curve detection. With each $S''(h) = 0$, there is an inflexion point of function $S(h)$ at h . At the intervals of h where $S''(h) < 0$, there must be salient curves of function $S(h)$, so the intervals of h are considered as height ranges of tree canopy layers.

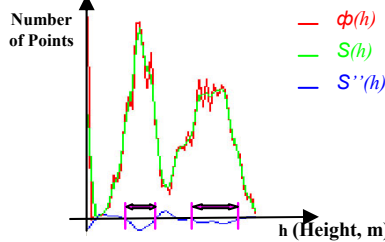


Figure 2. Relationship between $\phi(h)$, $S(h)$ and $S''(h)$, the ranges of canopy layers are extracted at the height intervals where $S''(h) < 0$

2.2.2 Attributes of Canopy Layers: The number of canopy layers in each study cell and the height range of each canopy layer are the main attributes derived from the vertical structure analysis. The range of a canopy layer starts from the height where the most rapid increase of point amounts occurred, the end of the range is marked at the height where the sharpest decrease of point amounts takes place (Figure 3.(a)).

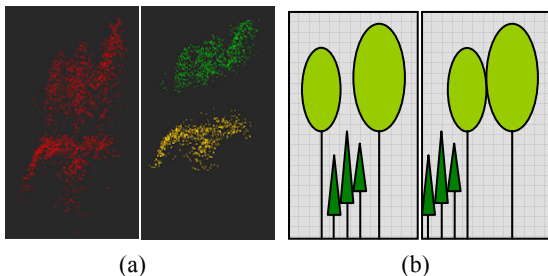


Figure 3. (a) Points within the ranges of the detected canopies with comparison of original point cloud; Left, Normalized point cloud; Right, Points within detected canopy ranges; (b) Two different forest stands with same height distribution probability density function; Left: Duple layer forest stand; Right: Single layer forest stand with trees of mixed height

As been illustrated in Figure 3 (b)., although there is no difference on height distribution of normalized points between the two cases, the spatial relationship of canopy layers is distinct. In the left case, the canopy layers overlap, such kind of situation can be considered as a real duple layer forest stand, on the contrary, the canopy layers in the right case are separated, this is actually a stand of trees with mixed heights. To detect the real duple layer stand, further studies on the spatial distribution of canopy layers are needed. This task is accomplished during the single tree extraction process.

3. SINGLE TREE EXTRACTION

3.1 2D Horizontal Projection Images

As being shown in Figure 4., a local voxel space is defined for each study cell, all the normalized points within the study cell will be resampled into the local voxel space.

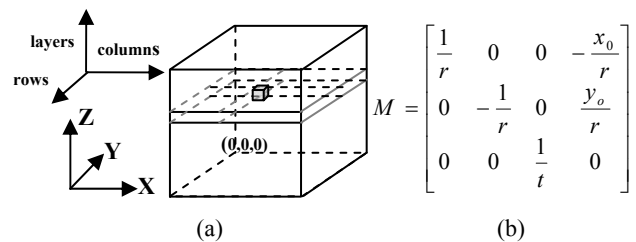


Figure 4. (a) Local voxel space with real world coordinate system (x,y,z) and voxel coordinate system (rows,columns,layers); (b) Definition of transformation matrix M

For the transformation of normalized points from real world coordinate system (x,y,z) to the voxel coordinate system (rows,columns,layers). A transformation matrix M is defined as figure 4.(b), of which: r represents the raster resolution of the horizontal surface in the voxel space; t represents the thickness of each layer in the voxel space; x_0, y_0 are the coordinates of the local origin, namely the x, y coordinate in real world coordinate system of the upper-left corner in the study cell; For each normalized point in real world $P(x,y,z)$, there is a correspondent point in voxel space $P'(row, column, layer)$, the relationship between P and P' can be defined with function:

$$[row \ column \ layer]^T = Round(M \times [x \ y \ z \ 1]^T)$$

According to the density of raw point cloud and the scale of r and t in transformation matrix M , it is possible that several normalized points are located within a same voxel. Take all the voxels of a single layer out of the voxel space, the voxels of the layer can be considered as pixels of an image. The number of normalized points within each voxel can be marked as the gray value of the correspondent pixel in the image.

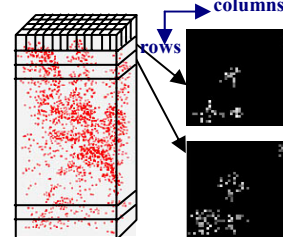


Figure 5. Normalized points in local voxel space and two examples of projection images of two vertical neighbouring layers of the voxel space

A 2D horizontal projection image of the selected layer is then generated (Figure 5.). The raw points of each individual tree crown will present a cluster feature on the horizontal projection image and the present of the cluster features is highly related with the horizontal resolution r and the thickness t of the voxel space. The values of parameter r and t in transformation matrix M rely on the density of the raw point cloud. According to our experiments, a horizontal resolution of 0.5 meter and a thickness of 2 meter are the ideal values for our dataset.

3.2 Extraction of Individual trees

The clusters on the horizontal projection image at each layer represent the distribution of tree crowns in the correspondent height level. Therefore an individual tree crown should be visible at the same location of several vertical neighbouring layers. The basic concept of single tree extraction is to trace the cluster features on the projection images from top to bottom through projection images at layers of different height levels.

3.2.1 Tree crown regions on 2D horizontal projection image: Potential tree crown regions in each layer are extracted based on the cluster features on the correspondent projection image. A hierarchical morphological opening and closing process with a group of predefined structuring elements (Figure 6.) is performed.

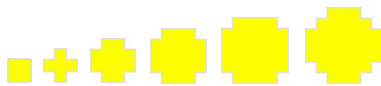


Figure 6. Structuring elements used in hierarchical morphological process

It can be presumed that the amount of raw points should be higher near the centre of each tree crown. Consider to the projection image, a higher gray value of a pixel represents a higher point amount in its correspondent voxel. Thus a higher significance should be assigned to the pixel with higher gray value and a larger neighbourhood of the pixel should be kept. The morphological process begins with the brightest pixels on the projection image, these pixels are taken as seeds and closed by the largest structuring element, then opened by the smallest structuring element, potential tree crown regions are then extracted based on the brightest pixels. Similar process is fulfilled with pixels of other gray value levels, the lower gray value the pixels have, the smaller structuring element is used for closing and the bigger structuring element is used for opening. Finally, potential regions from different gray value levels at same neighbourhoods are merged (Figure 7.). Levels of gray value are defined according to the histogram of the projection image at non-zero gray value area, of which highest level: $\alpha \geq 80\%$; middle level: $20\% < \alpha < 80\%$; lowest level: $\alpha \leq 20\%$.

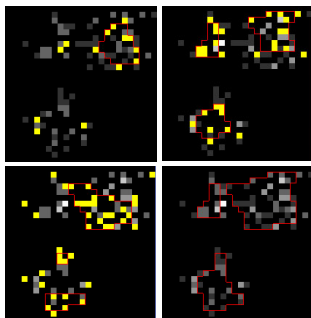


Figure 7. Hierarchical morphological process for tree crown region extraction from projection image; A

projection image is used as background, seed pixels are marked as yellow, contours of extracted tree crowns are marked as red. Upper left, Upper right, Lower Left: morphological process based on the pixels with highest, middle, lowest gray value level; Lower right: final result of tree crown extraction

3.2.2 Pre-order forest traversal: In computer science, forest traversal or more generally tree traversal refers to the process of visiting each node in a forest or tree data structure systematically. In our case, tree crown regions on the layers at different height levels can be considered as nodes at different levels of a forest data structure, crown regions on the top layer are the prime root nodes of the forest. A pre-order forest traversal process is fulfilled to visit all the crown regions of the forest.

Individual trees are extracted during the forest traversal process by grouping the vertical neighbouring crown regions from layers at different height levels. The main procedures of single tree extraction is illustrated in figure 8., a real case of single tree extraction is demonstrated in figure 9.. For each root node, namely the top region of each crown, the conditions of the existence of a child node, namely a vertical neighbouring crown region in next layer, are listed as follows:

$$\begin{aligned} A_i/A_r > C_a & \quad (1) \\ A_i/A_c > C_a & \quad (2) \\ D < \text{Min}(R_r, R_c) & \quad (3) \end{aligned}$$

where

- A_i = intersection area of root node and child node
- A_r = area of root node; A_c is the area of child node
- C_a = constant criteria in interval $[0.5, 1.0]$, for which 0.8 is an ideal value in our study case
- D = distance between centre points of root node and child node
- R_r = average radius of root node
- R_c = the average radius of the child node

All the three conditions are sufficient condition, two regions can be considered as neighbouring regions no matter which condition is fulfilled.

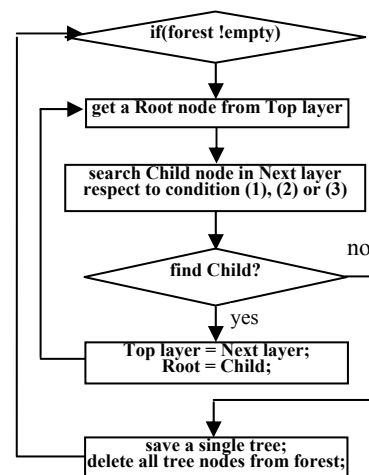


Figure 8. Main process of single tree extraction;

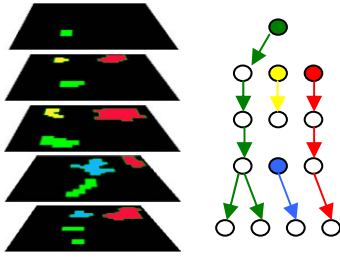


Figure 9. Demonstration of single tree extraction during a pre-order forest traversal process; Left: tree crown regions in different layers; Right: Result of single tree extraction, each tree is marked with a different colour, the root node of each tree is filled up with the same colour as the corresponding tree.

3.2.3 3D models of tree crowns: Each detected tree crown is described by an array of 2D tree crown regions in different layers at different height level. Since the layers in voxel space have certain thickness, 3D prisms can be constructed for the 2D crown regions in different layers with the thickness of layers as the height of the prisms. A group of 3D prisms at different height levels are then derived for each individual crown, and a prismatic 3D tree crown model can be reconstructed by a combination of all the tree crown prisms (Figure 10.).

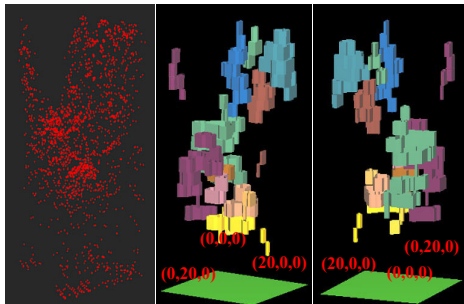


Figure 10. VRML(Virtual Reality Modeling Language) prismatic model of individual tree crowns within a single study cell with comparison of normalized point cloud; Left: Normalized raw points in a single study cell; Middle & Right: VRML models of individual tree crowns in the study cell visualized from different view directions, individual tree crowns are marked with different colours. The 3D models have the same vertical resolution with the local voxel space.

3.2.4 Features of study cell and individual trees:

1. For an individual tree the following parameters are available:
 - Height of the tree;
 - Height range of the crown;
 - Diameters of the crown at different height levels;
 - The largest diameter of the tree crown and its correspondent height;
 - Volume of the crown.

2. For a study cell, beside the number of individual trees, the number of crown layers is examined according to the spatial distribution of the extracted crowns. If there is an overlapping between individual crowns at different height levels, the study cell is considered as duple layered. This is a supplemental process for the study cells in which more than one canopy layers have been detected according to the vertical structure

analysis. After the analysis for all the study cells, the distribution of duple canopy layers in the whole study area can be mapped (Figure 11.)

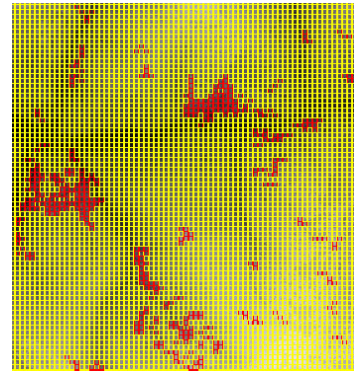


Figure 11. Map of duple canopy layer stands in one of the study area (Kuernacher Wald); Study cells with two canopy layers are marked as red; Study cells with single canopy layer are marked as yellow;

For 3D single tree extraction, a comprehensive reference data set based on field measurements is still missing. Coarse evaluations are based on ocular inspections of the raw data cloud points, aerial photographs and field information.

4. CONCLUSION

The statistical method seems to be efficient and reliable in detecting the existence and height range of canopy layers due to the first visual checks. The drawback is that it is incapable in distinguishing a real duple canopy layer structure and a single layer structure with trees of mixed heights. The existence of duple canopy layer structure is examined during the single tree extraction process according to the spatial distribution of canopy layers.

For the single tree extraction, the advantage of our algorithm is that not only the individual trees whose crowns are at the top canopy layer, but also the lower trees whose crowns are covered by the top canopy layer are extracted. The crown contours extracted from different height level of an individual tree crown will provide a higher approximation between the 3D crown model and the reality. The main problems still faced are due to the trees with big crowns and the conjunct neighbouring trees. For big tree crown with more than one crown peak, the crown might be split into more than one individual crowns. Trees whose crowns are tightly conjunct might be considered as a single tree. Another disadvantage of current algorithm is that the segmentation of study cells might split the trees along the border of the cells.

The main influence factors on the quality of the 3D single tree extraction algorithm are the density of the raw point cloud and the stand situation of the forest. Higher point density will improve the accuracy of tree extraction. Better result can be expected for a lower canopy closure forest stand.

Despite the mentioned challenges, the outcomes of recent single tree extraction algorithm are encouraging. Further studies will concentrate on the improvement of the single tree detection and modelling process, utilization of full waveform data could be helpful for the achievement of better tree crown models, and an enlargement of study cell size or a substitution of the raster grid by a moving window for study cell segmentation would reduce the over split of the trees along the border of each cell.

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