LIDAR POINT CLOUD BASED FULLY AUTOMATIC 3D SINGL TREE MODELLING IN FOREST AND EVALUATIONS OF THE PROCEDURE

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ABSTRACT:

A whole procedure of fully automatic 3D single tree modelling based on LIDAR point cloud is introduced in the paper. The evaluation of the procedure is then delivered by verifying the modelling results with field collecting data in sample plots. With the procedure, individual trees are extracted not only from the top canopy layer but also from the sub canopy layer, 3D shape of the extracted individual tree crowns are reconstructed, from which important parameters such as crown height range, crown volume and crown contours at different height levels can be derived. For the evaluation of the performance, the procedure is implemented with LIDAR data of 25 sample plots where detailed field inventories have been accomplished. Results of the procedure such as the number of individual trees in each sample plot, the location of the detected individual trees are verified by a statistical comparison with the field collecting data. Further analysis on the evaluation results is delivered at the final.

1. INTRUDUCTION

The individual tree levelled forest investigation has always been of high interest in forest management. As a relative new member of remote sensing instruments, airborne laser scanning, namely LIDAR, is especially suitable for reproducing the three-dimensional (3D) structure of forest stand due to its capability of 3D measurements with high accuracy. Several approaches of LIDAR based individual tree extraction in forest have been achieved during the past few years. The majority of the existed algorithms are DSM (Digital Surface Model) based (Hyyppä 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 Hyyppä (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. Further more, a new full-waveform based algorithm for detecting tree stems has been delivered by Reitberger et al. (2007).

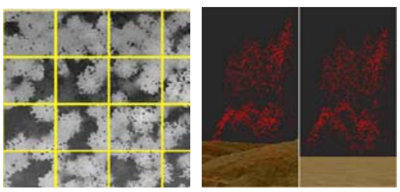
The procedure of LIDAR raw point cloud based 3D single tree modelling has been firstly published by Wang et. al. (2007), an improved version will be introduced in the second chapter of this paper. Another main interest of this paper is to evaluate the performance of the procedure. Accuracy verifications of the processing results in several sample plots are presented in the third part of the paper. Chapter 4 is for the analysis of the evaluation results. The LIDAR data as well as the field inventory data in sample plot being used in this paper was collected for a project on the utilization of LIDAR technology in forest inventory, financed by Polish General Directorate of State Forests and coordinated by Faculty of Forestry, Warsaw University of Life Sciences.

2. 3D SINGLE TREE MODELLING

2.1 Pre-Processing of LIDAR Raw Point Could

The Pre-processing contains two steps. Firstly, the subdivision of data in area of interest, secondly, the generation of normalized point could.

Due to the computational cost of memory and storage, it is not necessary to analyse all the points in a large area in one step. The study area can be divided into several small grids accordingly (Figure 1.(a)). Further processes are concentrated with each cell separately. The favored size of a single study cell can be flexible from 10m*10m to 200m*200m according to our own experiences.



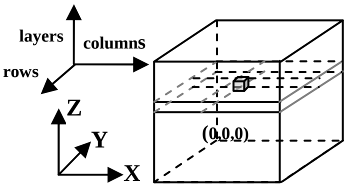
(a) (b)

Figure 1. (a) Subdivision of a study area, study cells are marked with yellow lines over a DSM; (b) Comparison between original LIDAR raw point cloud and normalized point cloud; Left: original raw point cloud over a DTM; Right: normalized point cloud over a zero height level surface

The procedure is based on the analysis of the object height of the captured points. Thus, the influence of terrain must be eliminated. A raster DTM (Digital Terrain Model) is used for the normalization of raw point heights. As shown in Figure 1.(b) 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. (b) Right). Point heights of the normalized point cloud represent the absolute heights of the objects. The DTM we used is generated from the raw point cloud by TreesVis, a software for LIDAR data processing developed by FeLis (Weinacker et al., 2004).

2.2 2D Horizontal Projection Images

Concentrate with a single study cell, a local voxel space is defined. All the normalized points within the cell will be resampled into the local voxel space. The relationship between the voxel space coordinate system(rows,columns,layers) and the real world coordinate system(x,y,z) is illustrated in figure 2. (a).



(a)

$$M = \begin{bmatrix} \frac{1}{r} & 0 & 0 & -\frac{x_0}{r} \\ 0 & -\frac{1}{r} & 0 & \frac{y_o}{r} \\ 0 & 0 & \frac{1}{t} & 0 \end{bmatrix}$$

(b)

Figure 2. (a) Local voxel space, the voxel coordinate system (rows,columns,layers) and its relationship with real world coordinate system (x,y,z); (b) Definition of transform- ation matrix ***M***

For the transformation of normalized points from real world coordinate system to the voxel coordinate system, a transformation matrix ***M*** is defined as figure 2.(b)

where r = raster resolution of the horizontal layers
t = thickness of each horizontal layer
x_o, y_o = coordinates of the local origin, namely the *x*, *y* coordinate in real world coordinate system for the upper-left corner of the study cell

For each normalized point in real world *P(x,y,z)*, there is a correspondent voxel in voxel space *P'(row, column, layer)*, the relationship between *P* and *P'* can be defined by function:

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

A series of 2D images is introduced as an instrument for recording the resampling results in the voxel space. 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. A 2D horizontal projection image of the selected layer is then generated (Figure 3.).

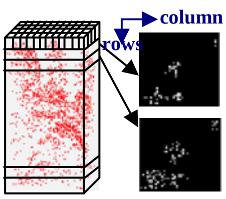


Figure 3. Normalized points in local voxel space and two examples of horizontal projection images of two vertical neighbouring layers in the voxel space

The raw points of each individual tree crown will present a cluster feature on the horizontal projection image and the form of the clusters is highly related with the horizontal resolution ***r*** and the thickness ***t*** of the voxel space. Further discussions on these two parameters will be given in the final part of this paper.

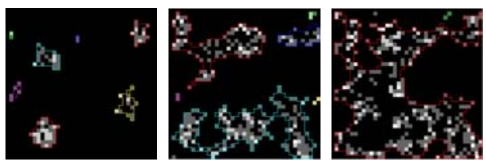
2.3 Modelling of Single Tree Crowns

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 different height levels.

2.3.1 Delineation of individual tree crown contours: a hierarchical morphological opening and closing process with a group of structuring elements (Figure 4) is performed to delineate the tree crown regions from the projection images.

Figure 4. Structuring elements used in hierarchical morpho-logical process

It can be assumed that the amount of raw points should be higher where a tree crown presents. Considering 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. Levels of gray value are defined according to the histogram of the projection image at non-zero gray value area, of which highest level: α>=80%; middle level: 20% <α<80%; lowest level: α<= 20%.



(a) (b) (c)

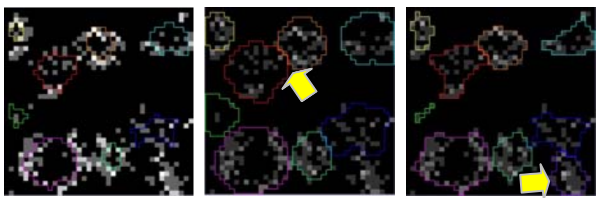
Figure 5. A real case of hierarchical morphological based crown contour extraction at different height level, (a) crown contours at top layer; (b) crown contours at lower level; (c) crown contours at the middel of canopies;

Figure 5 illustrates a series of crown contours at different height levels delineated by the hierarchical morphological algorithm. It is obvious that the contours of individual crowns are easy to delineate at the beginning (Figure 5. (a)) because of the concentration of Lidar points at tree tops. Things turn to be difficult when the process goes to lower layers since crowns are not solid with Lidar points and neighbouring crowns conjunct, individual crowns are hardly to detect in these cases (Figure 5. (b)). The situation can be even worse at the height level where all the neighbouring tree crowns touch each other (Figure 5.(c)), the clusters on the projection image might be considered as a whole thus the delineated contour is useless. To solve this problem an improvement of the hierarchical morphological algorithm is necessary.

2.3.2 Improved tree crown contour delineation: The process of this stage is enlightened by the DSM based single tree delineation algorithms that are generally based on morphological pouring or watershed.

The most significant section of the morphological algorithms is to stop the region growing when the neighbouring regions touch each other. A Simulation of pouring is fetched in the tree crown contour delineation process. As being presented in figure 6. (a), crown contours from the higher height level is now taken as a reference. The crown contours from the upper layer is dilated by a certain radius ***D***, the enlargement is stopped when the neighbouring regions conjunct. The yellow arrow in figure 6.(b) points the position of the conjunctions. Paramter ***D*** is acturally a very influential factor of the whole procedure, its impact on the final results will be discussed later in the final chapter.

The hierarchical morphological algorithm is parallel implemented inside and outside the enlarged reference regions. Compare figure 6.(c) to figure 5.(c), contributions of the reference regions are distinct. The utilization of reference regions will not influence the emergence of new tree tops at sub height level due to the parallel process in and out-side the reference regions. Yellow arrow in figure 6.(c) indicates the appearance of new tree top.



(a) (b) (c)

Figure 6. Simulation of pouring, (a) Crown regions from upper layer as reference regions; (b) Growing of reference regions, split when neighbours overlap; (c) Crown regions detected in and out side the refeence regions;

2.3.3 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 to be 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.

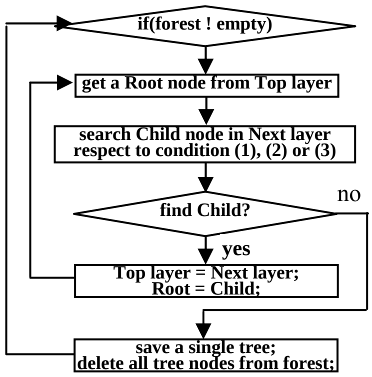


Figure 7. Main process of single tree extraction

Individual tree crowns are extracted during the forest traversal process by grouping the vertical neighbouring crown regions from layers at different height levels. The main process of the single tree extraction is illustrated in figure 7. 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:

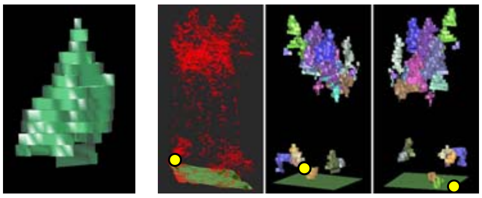
(1) Ai/Ar>Ca
(2)Ai/Ac>Ca
(3) D<Min(Rr,Rc)

where Ai = intersection area of root node and child node
Ar = area of root node; Ac is the area of child node
Ca = constant criteria in interval [0.5, 1.0], for which 0.8 is an ideal value according to the experiments
D = distance between centre points of root node and child node
Rr = average radius of root node
Rc = the average radius of the child node

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

2.3.4 3D modelling of tree crown: 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 crown model can be reconstructed by a combination of all the crown prisms (Figure 8. (a))



(a) (b)

Figure 8. (a) VRML (Virtual Reality Modelling Language) prismatic model of an individual crown; (b) VRML prismatic model of individual tree crowns in a single study cell compare with raw points; Left: Raw points in a single study cell over DTM, local origin of the cell is marked with the yellow dot; 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.

Figure 8. (b) shows the final result of 3D single tree modelling in a study cell. For an individual crown, 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.

3. PROCEDURE EVALUATION

The main object of the procedure evaluation in this stage is to verify the accuracy of the detected trees and to investigate the most influential factors of the procedure. Field inventory results of sample plots are employed as verification reference. The concept is firstly to check how many field measured trees being detected successfully in the simple plots, then to inspect the main impact factors of the performances.

3.1 Datasets

3.1.1 Field collecting data: all together 30 sample plots located in Milicz Forest District, Poland, in which detailed field measurements have been delivered with geodesic (radius 5m~7m) methods, are taken as the targets of the investigation.
Map of the sample plots is illustrated in Figure 9. The area of Milicz forest district is 26250 ha, where 96% (25362 ha) is covered by forest. The dominant tree species in the region are: Scot pine (*Pinus silvestris*) -76%; Oak (*Quercus sp.*) - 9%; Beech (*Fagus silvatica*) -4,7%. The average stand volume is 290 m^3/ha and stand age is from 5 to over 100 years.
Parameters delivered by field works for each sample plots are:

- DBH of all trees
- Height of all trees from different layers separately for each species with SUNTO instrument
- Position of each tree top and trunk (x, y) with SUNTO instrument
- Diameters of 8 directions of tree crowns. Instrument with mirror system was used so that the boundary of crown can be visible from the ground.

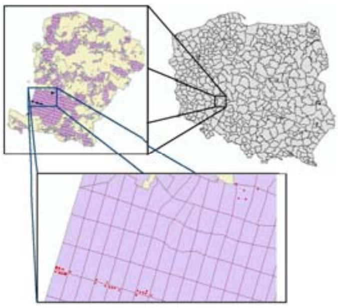


Figure 9. 30 sample plots in Milicz Forest District, Poland.

3.1.2 LIDAR data: The data was collected by TopoSys (Falcon II System) in 2-3 May, 2007, with a flight altitude of 700 m. The scan angle of the Falcon system is 14.3 degrees +/- 7 degrees. Footprint size of the laser beam is 0.7 m, first and last echo of each beam were recorded. The point density for first echo is usually 7point/m^2 and 7~8 point/m^2 for last echo. There is a strong irregularity of spatial distribution of the collected raw data points (figure 10).

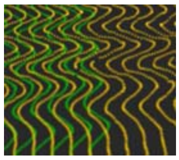


Figure 10. View of Falcon system LIDAR raw data pattern

According to a previous investigation made by ZSIPiGL, our cooperator in Poland, the field collecting data matches the LIDAR data quite well. Datasets from 25 out of the 30 sample plots were merged of 100% certainty between the field measurements and their correspondent nDSM (Normalized Digital Surface Model), which is calculated from LIDAR raw points by TreesVis, a software developed for LIDAR data visualization and analysis by FeLis.

3.1.3 Automatically detected trees: Raw points from both first and last echo are taken into the consideration.
Centre point of the crown region at the top height level of a detected individual tree is reckoned as the treetop
Shp file is generated for each simple plot, which is more straightforward for the further evaluations. All the detected treetops in a plot are saved into a feature layer with the related parameters derived by the procedure such as the height range and the volume of the detected tree crown as their attributes.

3.2 Accuracy evaluation of single tree detection

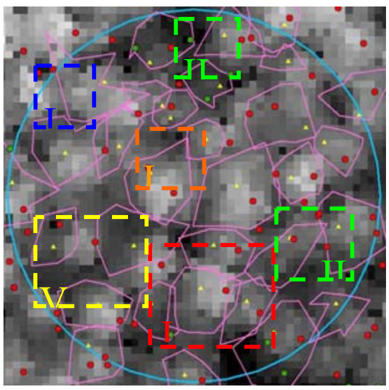


Figure 11. A real case (plot 20) of accuracy evaluation

The 3D single tree modelling procedure has been implemented with LIDAR raw data from 25 simple plots where the LIDAR datasets and the field collecting datasets fit with high reliability. Figure 11 shows a real case of the accuracy evaluation. The grey value image at the background is the nDSM of the sample plot and the big blue circle is the boundary of the plot. Yellow triangles mark the treetops measured in the field and the pink polygons are the manually delineated tree crown contours during the field works. Coloured dots are treetops of the automatically detected individual trees, among which reds mean the height of treetop is greater than 20m and greens are lower than 20m.

The verification is based on the spatial relationship between the field measured treetops as well as the crown contours and the automatically detect individual treetops. nDSM is another useful reference for inspecting the correctness of both automatically detected and field measured results. Five different cases have been defined to describe the accuracy of the detected treetops:

- **Hit**, there is one and only one detected treetop within a measured tree crown, the height difference between the measured treetop and the detected treetop is smaller than 3m, e.g. case I marked with red rectangle in figure 11.
- **Hit-probably**, there is one detected treetop at the same height level nearby a measured tree crown and with a high probability of being the top of same measured tree respect to the nDSM, e.g. case II inside the orange rectangle of figure 11.
- **Split**, there are more than one neighboured detected treetops within a measured tree crown and according to the nDSM there is no break line of height change within the measured tree crown such as case III in green rectangle of figure 11.
- **Miss**, there is no detected treetop inside or nearby the measured tree crown (case IV in blue rectangle upper left of figure 11.).
- **Uncertain**, as the main reference data, sometimes it is the field measurements, from which the suspicious has been raised. Case V in figure 11. marked by the yellow rectangle gives an example: it is quite obvious that there are two isolated individual trees inside the rectangle according to the nDSM and the detected treetops, but only one tree was measured from the ground and the position of the measured tree seemed to be shifted.

3.2.1 Evaluation results of 25 sample plots: all the sample plots are firstly processed by the procedure with default parameter settings:

- Transformation matrix ***M***: ***r*** = 0.5m, ***t*** = 1m;
- Dilation radius of crown growing: ***D***= 2m;

The evaluations of the primary processing results are listed in table 1., in which numbers of the different evaluation cases as well as their percentage in each simple plot are recorded.

Plot	Field	Hit	Hit-P	Split	Miss	uC
2	21	12	4	2	-	3
	100%	57%	20%	9%	-	14%
3	13	9	2	2	-	-
	100%	70%	15%	15%	-	-
4	7	5	-	2	-	-
	100%	72%	-	28%	-	-
5	6	4	1	1	-	-
	100%	68%	16%	16%		
6	14	8	2	-	2	2
	100%	58%	14%	-	14%	14%
8	21	14	4	1	2	-
	100%	67%	19%	5%	9%	-
9	22	6	6	1	3	6
	100%	27%	27%	5%	14%	27%
10	16	9	3	2	-	2
	100%	56%	18%	13%	-	13%
11	20	10	3	-	3	4
	100%	50%	15%	-	15%	20%
12	24	3	5	-	16	-
	100%	13%	20%	-	67%	-
13	20	9	3	-	5	3
	100%	45%	15%	-	25%	15%
14	28	7	2	-	16	3
	100%	25%	7%	-	57%	11%
15	21	13	2	-	6	-
	100%	62%	9%		29%	-
16	21	12	2	-	7	-
	100%	57%	10%		33%	-
17	13	8	1	1	3	-
	100%	61%	8%	8%	23%	
18	23	3	1	-	19	-
	100%	13%	4%	-	83%	-
19	30	20	6		2	2
	100%	66%	20%		7%	7%
20	31	17	4	3	3	4
	100%	54%	13%	10%	10%	13%
21	17	3	-	6	8	-
	100%	18%	-	35%	47%	-
23	38	7	-	1	30	-
	100%	18%	-	3%	79%	-
25	24	15	3	2	-	4
	100%	63%	13%	8%	-	16%
27	20	15	1	2	1	1
	100%	75%	5%	10%	5%	5%
28	22	9	6	2	-	5
	100%	41%	27%	9%	-	23%
29	25	13	6	3	-	3
	100%	52%	24%	12%	-	12%
30	18	9	5	-	2	2
	100%	50%	28%		11%	11%

Table 1. Evaluation report of primary processing results; (Field captions: Plot – plot number; Field – number of field measured trees; Hit – number of Hit; Hit-P – number of Hit-probably; Split – number of split; Miss – number of Miss, uC – number of Uncertain;

The performance of the procedure is generally satisfactory (Hit>60%, Hit+Hit-P> 80%) in matured stands (age >90) for both deciduous (Oak, Beech) dominated (plot 2~5) and conifer (Pine) dominated (plot 7~11, 25~30). But the result can also be extremely worse in the younger stands such as plot 12~17 (age~60) and plot18, 23(age<50). Plot 18 and 23 are extremely difficult since the average height of the trees smaller than 15m. Unique parameters are definitely not capable for all the different stands especially the younger ones. Table 2. lists the improved results by modifying parameters due to stand situations, detailed analysis on the influence of the parameters will present later.

Plot	Field	Hit	Hit-P	Split	Miss	uC
12	24	10	5	6	3	-
	100%	42%	21%	25%	12%	-
13	20	7	4	6	-	3
	100%	35%	20%	30%		15%

14	28	15	4	3	3	3
	100%	54%	13%	11%	11%	11%
15	21	16	2	1	2	-
	100%	75%	10%	5%	10%	
16	21	17	2	-	2	-
	100%	80%	10%		10%	
17	13	10	-	2	1	-
	100%	77%	-	15%	8%	-
18	23	4	2	-	17	-
	100%	17%	9%	-	74%	-
21	17	8	2	5	2	-
	100%	47%	12%	29%	12%	-
23	38	12	6	9	9	2
	100%	32%	16%	24%	24%	4%

Table 2. Improved results by adjustments of parameter settings respect to stand of plots

4. CONCLUSION

4.1 Inspection of failures

The main failures the procedure facing are the Miss and the Split, both have a high relevant with the stand situation, namely, the species, the age and the density of trees.

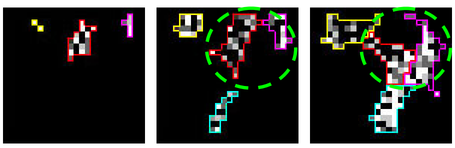
4.1.1 Miss: which occurred more frequently in mixture and dense stand and more often with lower trees at first canopy layer is generally caused by a tightly conjunction of the neighbouring crowns.

(a) (b) (c)

Figure 12. Case I, a real case of Miss; (a) crown regions at top height level (25m); (b) crown regions at 24m; (c) crown regions at 23m

The main reason of missing trees is quite obvious in Figure 12.(b) where the voxels in the red circle are actually belonged to a new tree, which can be proofed by the correspondent features at lower height level (Figure 12. (c)). Once the treetop is missing, the whole tree will be lost and will be reckoned as part of its neighbouring tree. Missing treetops that are too near or even adhere to their neighbours takes 90% of Miss according to our inspections. Younger trees at first canopy layer especially younger conifers in mixed stand are the main population of Miss.

4.1.2 Split: which is more related with the tree species always arose from deciduous trees whose crowns are wide dispersed.



(a) (b) (c)

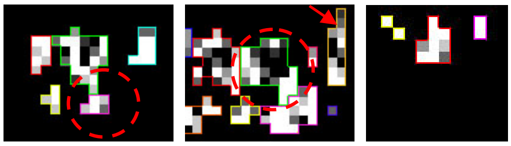
Figure 13. Case II, a real case of Split; (a) crown regions at top height level (25m); (b) crown regions at 24m; (c) crown regions at 23m

Split is a greater challenge than Miss, especially in a mixed stand. Figure 13. demonstrates the disturbance caused by mixed species near to each other. In Figure 13 (a), three treetop regions have been delineated. There is no difference between the yellow one and the magenta one, neither the shape, the size nor the distance to the red. Trace the crowns to lower height levels, it can be manually recognized that the red and the magenta crowns are actually belonged to a single deciduous tree (Figure13. (b), (c)). The problem attaches strongly to the species, almost all the Splits in the sample plots take place with the deciduous trees.

4.2 Impact of process parameters

As being proved in the evaluation process, outputs of individual tree modelling can be improved by an adjustment on the control parameters of the procedure due to a pre-knowledge of the stand situation. The impacts of different parameters on the modelling results have also been investigated.

4.2.1 Horizontal scale of voxel space: decided by the resolution $\boldsymbol{r}$ of transformation matrix $\boldsymbol{M}$ (chapter 2.2). A reduce of horizontal scale will produce a more compact feature of crowns. The projection images in Figure 14. are generated with $\boldsymbol{r}$ =1m. Compare with the projection images in previous chapters($\boldsymbol{r}$ =0.5m), the change of features is remarkable.



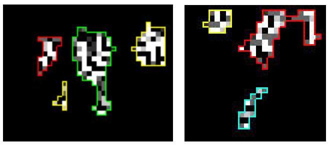
(a) (b) (c)

Figure 14. Projection images of voxel space with $\boldsymbol{r}$ =1m, $\boldsymbol{t}$=1m; (a) case I, 24m; (b) case I, 23m; (c) case II, 25m

The biggest advantage of a smaller horizontal scale is its benefits for delineating contours. Compare figure 14 (b) green with figure 12(c) green, the improvement of crown contour at lower height levels where vacuum of voxels appears at the centre of the crown is quite impressive. To the surprise, the problem of Miss can somehow be weakened, figure 14.(a) shows that the tree crown missed in figure 12.(b) is now detected. An increase of $\boldsymbol{r}$ means a horizontal enlargement of the voxels, which will cause a concentration of raw points in the voxels and will influence the morphological calculation results of crown region detection, but this kind of improvement relays on the distribution of raw points strongly thus not robust.

The original purpose of changing horizontal scale is to overcome the Split, but the effort seemed to fail (Figure 14.(c)). The other disadvantage is also notable, compare the yellow crown region marked by the red arrow in figure 14.(b) with Figure 12.(c) at the correspondent place, the single crown in figure 14.(b) is a false combination of two separated crowns, which is commonly caused by the smaller horizontal scale.

4.2.2 Vertical scale of voxel space: represented by the thickness $\boldsymbol{t}$ of transformation matrix $\boldsymbol{M}$ (chapter 2.2). A higher thickness will enhance the cluster feature of crowns since more vertically neighbouring points are gathered in the voxels.

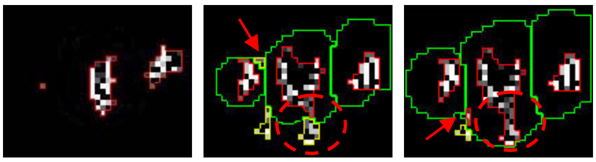


(a) (b)

Figure 15. Projection images of voxel space with ***r*** =0.5m, ***t***=2m; (a) case I, 25m; (b) case II, 25m

The most attractive contribution of a higher thickness is the improvement of deciduous crowns (Figer 15. (b)). But the drawback is comparably strong. Compare figure 15. (a) with figure 12. (b), the combination of a lower new treetop with an existing crown is enhanced, which means the opportunity of mixtures between new treetops and the existing crowns is also increased. Change the thickness will help to overcome the Split of deciduous trees especially in a matured stand when the crowns are broad and high, but it is not favored in younger stands and will raise the problem of missing lower trees.

4.2.3 Dilation Scale: crown growing radius ***D*** (chapter 2.3.2) is another powerful impact factor. Figure 16. illustrates the paradox of region growing with the reference crown regions.
The green circles in figure 16 (b) and (c) are the region growing results of the reference crowns from an upper layer (the red crown regions in Figure 16 (a)) with different values of dilation scale ***D***. Red circles in figure 16 (b) and (c) are the results of crown detection within the reference area, yellow ones are the results outside that are considered as new treetops.



(a) (b) (c)

Figure 16. Influence of Dilation radius ***D***; (a) crown regions at 25m (reference regions); (b) crown detection at 24m, ***D***=1.5m; (c) crown detection at 24m, ***D***= 2.5m

The dilemma of ***D*** is clear: with a smaller ***D*** (figure 16. (b)), the risk of missing new treetops can be decreased (in the ellipse), but the probability of split (pointed by the arrow) can be increased at the same time; while for a larger ***D*** (figure 16. (c)), the split may not happen to the existing (higher) trees but the influence on the new (lower) neighbouring trees is huge. The opportunity of both Miss (in the ellipse) and Split (pointed by the arrow) will rise. Smaller ***D*** is remarkably helpful for younger stands.

4.3 Conclusions

According to the primary verifications it is clear that the results of the point cloud based 3D single tree detection is quite promising. The average precision of extracting individual trees from middle aged (>60) mixed stand can reach to 55%(Hit) and around 75%(Hit+ Hit-P) after several adjustments of processing parameters due to different stand situation. The performance in mature (>90) stand is pretty satisfactory (84% in average) even in deciduous dominated plots. But the procedure is limited by the first and last echo data in younger stands (height <20m).
The determinant element of extracting trees correctly is to find out the proper treetops, which remains a challenge with deciduous and lower trees at first canopy layer especially in younger stand with high canopy closure. An adjustment of the control parameters would help to improve the results but no sole modification can solve all the problems at once, conflicts between Miss and Split are common when changing parameters. Several possibilities are available for promoting the procedure:

- A combination of voxel spaces at different scale. It is possible to union all the benefits from different scale such as the better deciduous crowns with larger ***t*** and better crown shape with larger ***r*** by implementing the procedure at different scales automatically.
- A non-constant ***D*** at different height level. The dilemma of ***D*** can be eased by a self-adapting process of the parameter due to the assumed crow shape for different species at different crown heights.
- Full waveform data is supposed to convey more detailed information on tree crowns and is expected to contribute a better result of 3D single tree modelling.

Further more, a 3D crown shape based classification between conifer and deciduous is also expectable from the future studies. As for the verification, the next concerned topic is the crown volume of the detected trees, which can hopefully be delivered by the further works on the issue.

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