ASSESSING THE 3D STRUCTURE OF THE SINGLE CROWNS IN MIXED ALPINE FORESTS

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ABSTRACT:

A method to automatically detect the tree crowns shape is presented in this paper. The study site is located in some mountainous parts of Friuli Venezia Giulia characterized by coniferous, mixed and broad-leaved forests with different population densities. The method, developed in an open source environment, is based on mathematical morphology operations that assess the cartographical position of the trees, as well as the height of the trees. Starting from single-extracted trees, a segmentation algorithm makes it possible to classify the laser point data as a subset of crown points. Then, the crowns are delineated by circular polygons centred on the geometric laser point barycentre. To enhance the quality of the calculated crown parameters (area, depth of insertion, volume), a statistical analysis of the height (z) frequency distribution was performed which allows the re-filtration of the low vegetation (border or under-canopy vegetation). The results have been validated using topographic total station data surveyed in situ, in 13 forestry sample plots with a total of about 550 reference trees. Considering the ecological diversity (complexity) of the chosen plots, the paper shows a high correlation between plot data and laser scanning extracted data, particularly in the coniferous areas, underlining the possibility of extending the fields of research to the study of the dominated vegetation under canopy.

1. INTRODUCTION

Monitoring of the forestry ecosystem is a current topic in the wooded resources sustainability debate. To characterize the vegetation from an ecological state and biomass content point of view, a detailed knowledge of the single tree population is needed. The assessment of such parameters is critical in terms of field operations and time needed. In this context, aerial laser scanning (LiDAR) is a promising survey technique for forestry inventories because of its capacity to directly assess the three dimensional structure of the forest due to the high point number of sampling per surface. Part of the research activities were carried out as a part of the INTERREG IIIA Phare/CBC Italia-Slovenia project entitled "Cadastral map updating and regional technical map integration for the GIS of the regional agencies by testing advanced and innovative survey techniques" at the University of Udine and in collaboration with the Geodetic Institute of Ljubljana. The research is focused on the use of Laser scanning data in the forestry field. In this context, the work was centred on the development of informative methodologies and algorithms to automatically assess the parameters characterizing the three dimensional structure of the single trees. The experiments have been carried out using original software developed in an open source environment (Beinat, Sepic, 2005) that allows the management of the laser point clouds. On the basis of this software, a specific tool of algorithms for forested areas has been implemented through which we can extract information about:

- the position, the number and the height of the single trees;
- the shape and the area of the single crowns (Barilotti, Sepic, 2006).

The data processing and the development of innovative algorithms for filtering, classification and modelling of laser scanning data are still being developed (Hyyppä et al., 2004). Further effort overall in the forestry field is needed because of the natural complexity of the single trees shape. Following the approach presented by some authors the determination of the population density and the crown shape over vast areas can be carried out by integrating laser scanning rasterized data with high resolution aerial images (Weinacker et al. 2004, Hyyppä et al., 2005). Other authors underline the advantages of using a direct analysis of the point clouds, avoiding interpolation on regularized grid of data (Tiede et al., 2005). As far as the study of three dimensional crown shape is concerned, the assessment of the insertion height is one of the most difficult parameters to assess. Due to this difficulty, some authors derive this geometric attribute from the LiDAR-extracted tree height, using empirical models of linear correlation (Pitkänen et al., 2004). However, this approach is only valid in a local setting and cannot be generalized because the crown shape varies depending on many factors: forest typology, population density, tree species, management type, soil typology etc. Moreover, the field survey of the crown parameters is not an easy procedure in terms of costs and time/operator needs and the results are not objective to determine. Starting from these considerations, the implementation of auto-adaptive methods to assess the crown three dimensional parameters is presented in this paper. Particular attention has been paid to verifying the quality of the results in different study plots in Alpine latitudes.

2. MATERIALS

The study areas are located in some mountain sectors of Friuli Venezia Giulia Region (N-E Italy) essentially characterized by coniferous forests (spruce, spruce-fir), broad-leaved forests (beech) and mixed forests. Within these areas some sub-zones

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of interest have been located and geo-referenced using topographic total station and GPS. This has allowed the precise and accurate determination of the coordinates of 13 circular forestry plots (transects) with radius ranging between 12 and 25 meters. The forestry characteristics of the studied plots are reported in Table 1.

Plot ID	n° of trees /ha	Area (m^2)	Management type	Age	Composition
FOA	663	450	stand	mature	mixed
FOB	531	450	stand	mature	mixed
MBA	619	450	stand	mature	mixed
MBB	1525	450	stand	juvenile	spruce
MBC	575	450	stand	juvenile	spruce
MBD	463	2000	stand	mature	spruce
PRB	840	450	stand	Juvenile/adult	spruce
PRC	752	450	stand	Juvenile/adult	spruce
SAA	336	2000	stand	mature	beech
TUA	538	700	conversion	juvenile	beech
TUB	862	450	conversion	juvenile	beech
TUC	553	450	conversion	juvenile	beech
VBA	1105	450	stand	juvenile	spruce

Table 1 – Summary of the geo-referenced forestry plot characteristics. Considering the different management type, age and composition of the 13 transects, 6 different forestry situations can be found.

These characteristics, describing the general ecological structure of the forests, give us an initial idea about the difficulty of characterizing the population with laser scanning and help to understand the expected morphometry of the single trees. The principal forest typologies studied are shown in Figure 1.

Figure 1 – Pictures of 4 different typologies of transect: juvenile stand spruce (MBC plot, upper-left); mature stand spruce (MBD plot, upper-right); juvenile converted beech (TUA plot, lower-left); mature stand beech (SAA plot, lower-right).

A field measuring campaign, performed within the 13 georeferenced transects, allowed to obtain detailed information on morphology and structure of each tree. Using a topographic total station we measured:

- The cartographic position of all trees (diameter at breast height more than 5 cm);
- The crown extension (4 sampling points for each one).

The crown base height was measured using portable instruments (length and angle). The diameter at breast height was also measured. The total data surveyed in situ using topographic instruments covers approximately 550 tree points and 2200 crown points. As far as the laser data is concerned, the principal characteristics of the dataset are reported in Table 2.

Plot_ID	Period of survey	N° of echoes	Local point density
FOA	november	F&L	2 pt/m2
FOB	november	F&L	2 pt/m2
MBA	june	Multiple	6 pt/m2
MBB	june	Multiple	7 pt/m2
MBC	june	Multiple	8 pt/m2
MBD	june	Multiple	10 pt/m2
PRB	november	F&L	1,5 pt/m2
PRC	november	F&L	1,5 pt/m2
SAA	october	F&L	4 pt/m2
TUA	may	F&L	2 pt/m2
TUB	may	F&L	2 pt/m2
TUC	may	F&L	2 pt/m2
VBA	june	Multiple	5 pt/m2

Table 2 – Summary of the laser data characteristics for each forestry transect.

As shown in the table, the datasets were surveyed in different periods. This must be taken into consideration, especially in the case of beech forests. In fact, as already shown (Barilotti et al 2006), the capacity of the laser beam to penetrate through the canopy depends on the presence (TUA, TUB, TUC plots) or non presence (SAA plot) of foliage cover. Some datasets were detected using a multiple pulse instrument (Optech ALTM 3100) that increases the capacity to sample the intermediate layers of the vegetation. In these cases we have plots with higher sampling points (5-10 pts/m^2) than those surveyed with a First & Last pulse laser scanner (Optech ALTM 3033; low density: 1.5 – 2 pts/m^2). The flight altitude was about 1000 m above ground and the laser beam divergence was 0.2 mrad according to the different survey campaigns.

The combination of the plot characteristics in terms of forest typology and laser metadata will be useful in order to understand the strengths and the limits of applying laser technology in forestry.

3. METHODS

A complete processing chain has been developed, starting with raw laser points as input data and ending with derived tree parameters for each single tree. The procedure is composed of a series of elaborations and transformations that can be schematically related to the following methodological aspects:

- Pre-processing of the raw laser data;
- Application of mathematical morphology algorithms, following a single tree approach, to extract the canopy apexes;
- Identification of the laser points belonging to the single crowns by means of a cluster analysis algorithm;
- Low vegetation sub-clustering using a local filtering method.

3.1 Pre-processing

The implemented step relating to the laser data pre-processing consists of an original algorithm that eliminates the points corresponding to the laser beam reflections under canopy from the dataset. The algorithm executes a first triangulation (Delaunay) of all points, then analyzes the height (z) difference between the vertexes of each triangle. Those vertexes whose height difference is greater than a threshold value (according to the minimal height of the forest) are eliminated. This allows the creation of a Digital Surface Model (DSM) without points under canopy and therefore introduces a higher degree of DSM adhesion to the external forest surface.

3.2 Tree extraction

The method proposed for the tree extraction is based on the morphologic analysis of the laser point distribution. To this aim the Top Hat algorithm, whose formulation is relative to the image elaboration theory (Serra, 1982), was implemented. Independently from the image typology, this mathematical function allows the extraction of the highest elements in the scale of the represented values (Andersen et al., 2001, Barilotti et al, 2005).
Extending the Top Hat concept directly to the pre-filtered point cloud, the method allows the detection of the set of points belonging to the top of the crown, avoiding the interpolation on raster images. The spatial position (x, y, z coordinates) of the apexes on the laser data can be obtained. It is assumed that the x,y coordinates of such apexes correspond to the cartographic position of the single trees. In some cases, because of the small height differences between nearest points belonging to the same crown, more than one apex can be marked for each tree. In order to diminish this kind of error, a checking algorithm that identifies and corrects the erroneously classified apexes (often localized into the crown edges) was introduced. The algorithm compares the height value of each extracted apex to the nearest laser points, using an opportune (user defined) search radius. If a point with a greater height value is found inside the searching window, it becomes the new apex.
Ground filtering is not an essential requirement in order to apply the morphological analysis, but it is however necessary to calculate the tree height. The filtering procedure has been done in this work using the software Terrascan™. The tree height is therefore calculated as the difference between the height value of the apex and the corresponding ground height. In accordance with the “National Forest Inventories” it is easy to exclude those uncertain apexes (trees) whose height is less than the given threshold (Barilotti, Turco, 2006).

3.3 Cluster analysis

In order to identify the single crowns a region growing algorithm was implemented. Starting from the apexes previously extracted, the algorithm classifies the vegetation points according to the criteria defined below:

- If the points located in the proximity of the starting apex are lower (height difference) than a fixed threshold, these are marked as belonging to the same cluster;
- When the same laser point is marked as belonging to different apexes (this is particularly true when the forest is characterized by close vegetation), the algorithm associates the point to the nearest apex;
- For each marked apex, the same procedure is iteratively applied.

An example of clustered data is given in Figure 2. The image highlights the auto-adaptive nature of the method. As can be noticed, the cluster shape (crowns) is not predefined and is closely related to the local morphology.

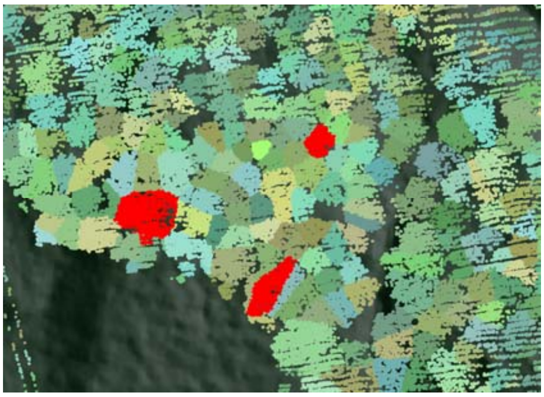

Figure 2 – Example of clustered laser data in a coniferous transect (MBD). The red coloured clusters emphasize the differences in terms of shape of the same species (spruce) in dependence of the ecological state.

3.4 Cluster re-filtering

Three different clusters are highlighted in red in Figure 2. One represents an example of a tree in a close forest while the others are located along the border. Even though the same species is present in the dataset shown, the resulting crown shape is very different in the three cases. The result is highly dependent on the efficiency of the tree extraction process.
Moreover, because of the presence of low vegetation in the dominated layer of the forest, a non optimal restitution of the crown geometry (area, base height) can be observed. This situation is outlined in the series of images in Figure 3 that show the three trees coloured in red of the previous figure isolated and visualized in a frontal view.
The height frequency distribution of the clustered points is reported (blue line) in the same sequence. The values are related to 1 meter spaced out classes along the x-axis. A specific analysis tool to automatically calculate the frequency distributions and the relative interpolating curves (red line) was implemented for each cluster.
As shown in the images (Fig. 3), the interpolated curves are very different in the three cases. The first kind of regression curve, in particular, indicates that the related tree is well clustered. On the contrary, the other curves (cases 2 and 3) indicate the presence of anomalies (higher point density in the lower classes of points) in the height frequency distribution. Such anomalies are evidently caused by the presence of dominated vegetation (understorey) and are not present when a mono-storey forest is surveyed. Starting from these considerations, it is therefore possible to characterize the interpolating curve through the study of the analytical function. Thus, we can use the height difference between the minimum

and the maximum points of the interpolated curve to find and define an automatic threshold of cluster re-filtering.

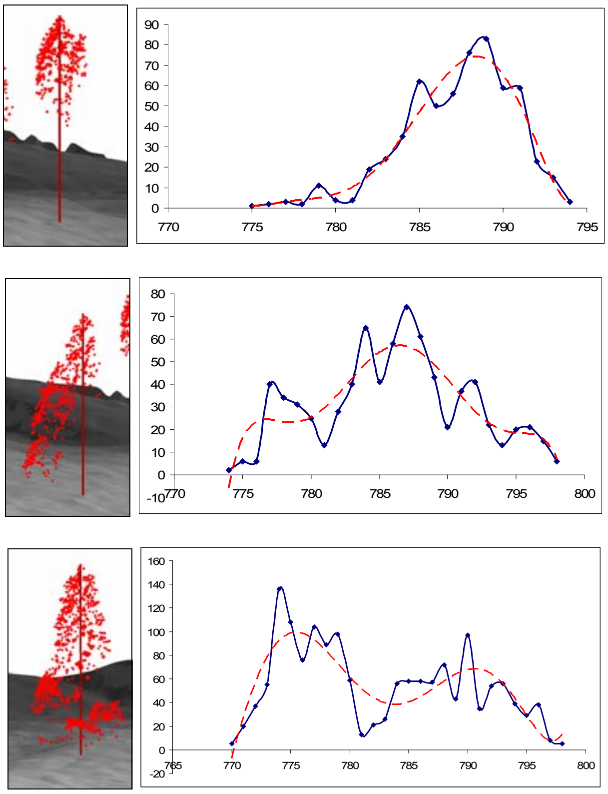

Figure 3 – Cases of clustered trees located in different positions into the forest. From the top to the bottom respectively: tree within close vegetation, two trees clustered together and tree with low vegetation. On the right the relative height frequency distribution of clusters is reported (blue line). For each frequency diagram, the 6° degree of the polynomial distribution is calculated (red line) and then it is used to re-filter the sub-clusters.

3.5 Crown delineation

The crowns are delineated using polygon circles whose parameters (centre and radius) are calculated analysing the planimetric coordinates of the points belonging to the clusters. The barycentre of the point distribution is assumed as being the centre of the crown. In most cases the centre of the circle does not correspond to the coordinates of the respective apex. This is particularly true in the case of beech forest. Each circle is drawn using a radius (r) equal to the following equation:

$$r = (X_{Max} - X_{min} + Y_{Max} - Y_{min}) /4$$

The equation allows the calculation of the average radius of the cluster distribution. The crown depth is calculated as the difference between the maximum height and the minimal height of the points belonging to the cluster. Moreover, the crown base height is calculated in terms of difference between the tree height and the crown depth (C_depth). The crown volume can be determined using the following equation:

$$C\_vol = CHM - [C\_area * (tree\_height - C\_depth)]$$

where C_area is the area of the delineated crown and CHM (Canopy Height Model) is derived by subtracting the height value of the DTM (Digital Terrain Model) at each pixel from the height value of the DSM.

4. RESULTS

The experimental results obtained by applying the methodological scheme shown above, were integrated into a G.I.S. (Geographic Information System) in order to create a database of forestry interest. The final result of the elaborations consists in two shapefiles for each input dataset (raw laser data) which contains information about trees and crowns summarized as follows:

- Cartographic position and height of the detected trees;
- Crown base height (alternatively the crown depth), crown area and volume.
- The field survey data is loaded into and managed by the same G.I.S. in order to compare and to check the quality of the LiDAR data extracted. The results are shown below.

4.1 Tree extraction

In Table 3 the results of the comparison between field trees and laser extracted trees are reported.

Field trees				LIDAR extracted trees			
Plot_ID	**Tot (ø>5)**	**Dominated**	**Dominants**	**Total Extracted**	**False positive**	**Total error**	**Correctly extracted (%)**
FOA	30	10	20	19	1	-2	90
FOB	24	8	16	15	3	-4	75
MBA	28	9	19	19	6	-6	68
MBB	69	37	32	19	0	-13	59
MBC	26	5	21	17	0	-4	81
MBD	91	11	80	77	4	-7	91
PRB	38	5	33	21	3	-15	55
PRC	34	5	29	27	6	-8	72
SAA	66	3	63	61	9	-11	83
TUA	38	18	20	42	17	5	75
TUB	39	12	27	33	3	3	89
TUC	22	1	21	19	2	-4	81
VBA	50	14	36	23	0	-13	64

Table 3 – Summary of field tree numbers and of the relative LiDAR extracted trees for each study plot.

In the table the trees whose diameter at breast height is significantly smaller to the surrounding ones are considered "dominated". However, the individuals whose crown does not reach the top of the canopy were measured during the field campaign. Moreover, the apexes which are located 3 meters beyond the field surveyed trees are considered "false positives". This is not generally a big error and could be further reduced applying more constraining parameters to the morphological analysis. We have to consider, however, that the method was applied in an automatic way (the same input parameters were used), independently from the typology of the forest and of the laser data differences. In any case, the forestry tool makes it possible to define and to optimize such parameters according to the previously mentioned variables. The percentage of correctly extracted trees varies meaningfully depending on the structure of the different forestry plots examined. Juvenile forests, with a high population density and a high percentage of small diameters, highlight the difficulty of using laser technology to characterize the population well. In these cases, underestimation is evident in terms of "dominated" trees. On the contrary, the results seem to improve significantly when the forestry plot is mature and mono-storey structured (even-aged). In this case, the percentage of extracted trees reaches high values in coniferous forests (80-92%) as well in broad-leaved forests (83%), meaning that the most interesting part of the forest (from an above ground biomass content point of view) is extracted anyway. The tree height value is calculated using the maximum height of the laser points (apexes). As far as this parameter is concerned, the method does not introduce relevant underestimations, which are possible using different approaches based on rasterized data.

4.2 Crown delineation

Table 4 reports the difference between the crown base height values measured on site and those extracted from the laser data. As far as this parameter is concerned, the correlations correspond to the well-extracted trees. In these cases, we isolated and analyzed the base height values connected to the different species within each plot, as the table shows.

ID	Plot_ID	Species	Cnt	Min	Max	Ave	SD
1	FO_A_B	Beech	4	-12,77	-0,07	-4,10	5,86
2	FO_A_B	Spruce	41	-13,27	11,00	-0,25	5,12
3	MB_A_B	Fir	8	-2,29	6,50	2,05	2,96
4	MB_A_B	Beech	4	-20,19	10,86	-5,52	12,7
5	MB_A_B	Spruce	21	-19,80	8,59	-0,74	7,43
6	MB_C	Spruce	17	-4,10	0,41	-1,07	1,28
7	MB_D	Fir	14	-16,00	9,15	-2,53	6,49
8	MB_D	Spruce	55	-18,57	4,32	-2,84	5,46
9	PR_B_C	Spruce	56	-15,93	1,71	-3,70	3,58
10	SAA	Beech	65	-9,97	12,03	-0,47	4,51
11	TU_A_B_C	Beech	79	-19,37	15,50	-5,54	8,65
12	VBA	Spruce	31	-15,84	11,32	-0,62	6,93

Table 4 – Summary of the crown base height analysis. The results are reported in terms of different species surveyed within each transect.

Excluding from the analysis process those sub-plots where the number of trees per species (Cnt) is insufficient to perform statistical analysis (row 1, 3 and 4 in Table 4), the result show:

- The minimum and maximum differences of base height for each forestry transect reach high values, respectively as a result of the difficulty of the laser beam in penetrating the canopy (negative values) and of the presence of outlayers (positive values);
- The average values (ave) are always negative, suggesting the tendency of the laser to overestimate the base heights (it follows that the crown depth and the volume are underestimated);
- The worse valuation concern those plots characterized by juvenile broad-leaved forests (ave of TU_A_B_C = -5,54), while there is an improvement in mature broad-leaved transect (ave of SAA = -0,47). However, this last area was surveyed in the absence of leaf cover;
- The best results correspond to the coniferous transect and don't seem to be affected by the age of the forest.

The average and the standard deviation values for those plots which are statistically significant are shown in graph form in Figure 4. The graph highlights that the average values of crown base height have a small overestimation (negative values) in most transects while the standard deviation has a high range of values.

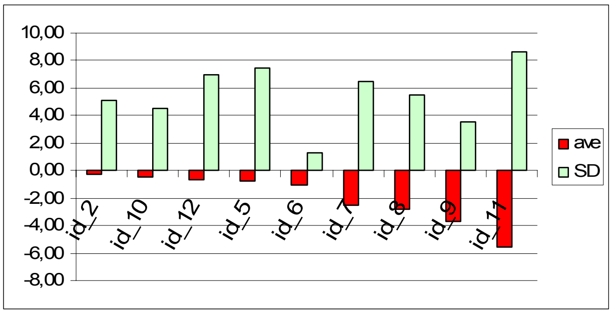

Figure 4 – Graphic visualization of the average and standard deviation of the values reported in Table 4 for those plots where the species number is significant.

The same analysis (average difference and standard deviation) was considered from a tree species point of view, without considering the plot characteristics. The values reported in Table 5 underline what can be expected in terms of crown estimation if a vast area of coniferous or broad-leaved forests is surveyed. While coniferous areas (spruce and fir) show little underestimation of the base depth (- 1,95 m < Ave < - 0,87 m), the base depth for beech trees is underestimate more (Ave < - 4 m).

ID	SPECIES	cnt	Min	Max	Ave	SD
1	Spruce	227	-19,80	11,32	-1,95	5,34
2	Beech	146	-20,19	10,86	-4,89	5,72
3	Fir	22	-16,00	9,15	-0,87	5,83
4	Pine	5	-13,93	11,51	2,62	9,85
5	Larix	4	-13,04	8,61	-1,05	10,32
6	Maple	3	0,83	8,69	4,01	4,14
7	Ash	2	0,79	2,04	1,42	0,88

Table 5 – Comparison of the crown base values between field surveyed and laser extracted data. The differences are summarized considering the different tree species.

Moreover, the application of the methods to multiple pulse surveyed data (cfr Table 2) doesn't seem to give better results, compared to the first & last data. The application of the re-clustering method previously mentioned would help to remove those return pulses due to the presence of low vegetation, like the example in Figure 5.

The quality of the crown area values depends substantially on the validity of tree extraction method. The qualitative comparison between the crown values measured on site and the clustered laser data correspond, especially in the case of the dominant vegetation layer. The reliability of the crown parameter estimates generally improves when laser point density is increased (2 pts/m^2 is the inferior limit of useful density for the described morphologic approach) but, in any case, this is influenced by the quantity of extracted trees.

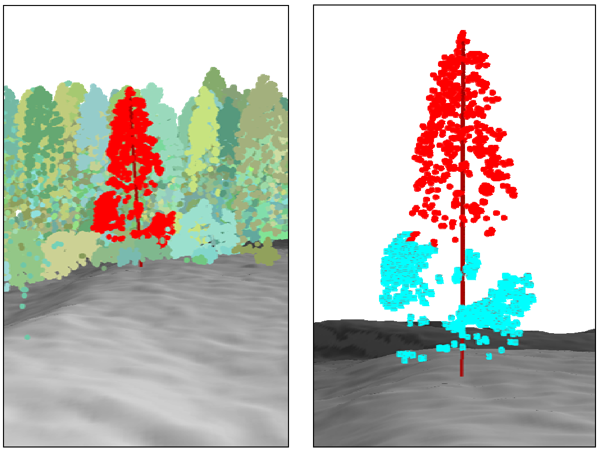

Figure 5 – Example of cluster re-filtering method to locally isolate the low vegetation (light-blue coloured points in the figure on the right) under dominant trees.

5. CONCLUSIONS

An innovative method of laser scanning data processing to automatically determine the crown parameters is proposed.
The Top Hat algorithm, implemented in Open Source environment, was used in order to determine the position of the tree apexes. Afterwards, using an original clustering algorithm, the single crowns were isolated and delineated. The results of the elaborations, opportunely integrated in GIS environment to create a database for the forestry sector, provide detailed information on the three-dimensional structure of the trees.
A field survey campaign in some mountainous geo-referenced plots highlighted the optimal performances of the method as far as the positioning and counting of the dominant trees (the main source of forestry biomass), in both coniferous and broad-leaved forests is concerned. Otherwise, a further work has to be done to improve the detection of the dominated vegetation.
As far as the correctly extracted trees are concerned, considering the difficulty of detecting the three dimensional tree parameters on site, the implemented method for crown delineation (particularly referred to the crown base height estimation) showed better results in the case of coniferous trees than in the broad leaved trees. As a matter of fact, in the latter case, the percentage of the laser beam penetration through the canopy is little because of the presence of very close vegetation.
Finally, a new method of cluster analysis, useful in filtering and isolating the dominated vegetation under canopy, was implemented. This last topic has to be verified in detail in the future, considering laser scanning data surveyed within multi-storey forestry plots.

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