DEVELOPMENT OF FILTERING, SEGMENTATION AND MODELLING MODULES FOR LIDAR AND MULTISPECTRAL DATA AS A FUNDAMENT OF AN AUTOMATIC FOREST INVENTORY SYSTEM

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ABSTRACT:

For a multitude of planning tasks, e.g. planning of power-lines, urban- and landscape planning or for forestry time-consuming on site inventories have to be done and thereby large costs arise. Therefore it is desirable to automate the inventory as far as possible. To make this aim realistic software has been developed, which provide a fundament for such types of automatic systems.
Three modules have been implemented and tested. First the **DTM/DSM filtering** – This task is mandatory to be able to estimate the height of all interesting objects. An algorithm has been developed based on an active contour model. It is similar to a method created by the Swedish Defence Agency. Secondly the **single tree delineation** is implemented as a process chain consisting of three main parts. Based on the DTM/DSM data and a pouring algorithm approximate tree crown boarder lines are calculated. Secondly geometric knowledge about form parameters and mutual geometric relations between tree regions are introduced to enhance the delineation. Finally a "ray-algorithm" is used to further improve the delineation result. The third module, the **tree species classification** consist on a linear stepwise discriminant analysis algorithm using both laser and multi-spectral data and finally a form fitting of extended superquadrics based either on raster or original laser data is tested as tool for the tree classification and modelling.

1. INTRODUCTION

1.1 Forest inventory

Forest inventory is a very time-consuming task where also a large number of employes are involved. With regard to curt financial resources and the ongoing reorganisation within the German forest administrations, it become necessary to think about how a new method for forest inventories, which of course should be faster and cheaper, could look like.
In the last years the lidar technique has developed quite a lot and is successfully used for e.g. DTM calculation, power supply line registration and in other fields. Therefore, it seems promising to develop methods, which can be used as a fundament for a semi- or even fully automatic inventory system using lidar and multi-spectral data simultaneously.
A complete processing chain has been developed, starting with raw laser data as input and ending up with derived tree parameters for each single tree. The chain include the calculation of DSM/DTM, the delineation of single trees, tree classification and also 3D-modelling.

1.2 Study Areas

The test areas are located in Southwest Germany close to the city of Freiburg. They were selected to cover as many different characteristics of forest stands as possible. The "Mooswald" area is situated Northwest of Freiburg. It covers a planar region of 20ha at a height of about 200 m above sea level. With exception of one stand of 30-years-old douglas firs, it consists of mixed deciduous forests. The dominating species are English oak and hornbeam, with a changing share of other deciduous species like red oak, ash or Norway maple. The forest is rich in structure: canopy gaps alternate with very dense or double layered parts and trees are of very uneven age. The other study site, "Günterstal", is in the Southeast of Freiburg. It is a mountainous area of 70ha with a height of 500 to 800m above sea level. The vegetation consists mainly of mixed mountain forest, mostly beech (60%), fir (25 %*)* and spruce (10 %). Most stands are of uneven age, many have got an understory.

1.3 Data

During spring and summer 2002 lidar data are acquired by TopoSys using the FALCON-system (TopoSys, 2003). This measurement unit sends out laser pulses with 127 glass fibres, with a pulse frequency of 83 kHz. First and last echos are recorded. An average altitude of 400m in Mooswald and of 850m in Günterstal has been flown. However, due to the structure of the sensor the laser spots are placed in a very irregularly line pattern. Each 3D laser point has a relative precision in the xy-plane lower than 0.5m and in height it is lower than 0.15m.
As reference data, stem coordinates, diameter at breast height and crown projections of 98 sample trees have been measured terrestrially in "Mooswald" in five plots. In "Günterstal" crowns have been delineated manually in CIR stereo-models on approximately 80% of the area. Again five plots (each of 100 * 100 m²) are chosen randomly within this test area.

2. MODULES

The software consist out of three main parts. In the first module the filtering of the laser raw data is done in order to estimate the DTM and DSM. Thereafter single tree delineation is following and finally modelling and classification of trees into the two groups conifer and deciduous trees is finishing the processing chain. In the following chapters the used methods are presented.

2.1 DTM/DSM filtering

Active contour theory is the base for the implemented filtering algorithm. The algorithm works similar as the method developed by (Elmqvist, 2000) and (Persson, 2002). Detailed

information concerning the use of active contours is found in (Blake 1998) and for the surface filtering see (Elmqvist, 2002).
The filtering algorithm starts with the creation of a raster area, using pixel sizes in relation to the density of the given raw data points. DTM/DSM filtering done in a second step is based on these raster surfaces.

2.1.1 From Raw-Data to Raster Area

Three raster surfaces with identical dimensions are created – an active surface, a punch surface and a mask surface. Each pixel of the punch surface is filled with the lowest or the highest 3D point, depending on whether the DTM or the DSM is calculated. The mask surface is used to save attributes necessary for the minimisation process, which is done to estimate the final active surface. After the initial creation of these surfaces the raw data are no longer needed for the minimisation process and are deleted from the memory. Figure 1 shows settings of the punch surface.

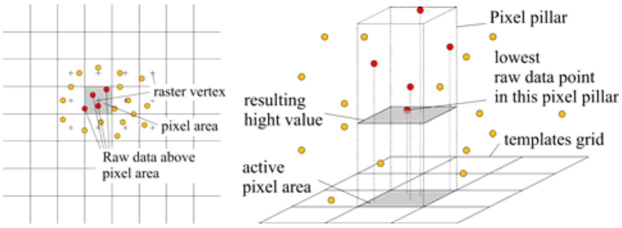

Fig.1: (Left) Raw data points falling into one pixel area; (Right): Shows the active surface (lowest) and a punch pixel whose height is defined by the lowest raw data point.

2.1.2 Active surface fitting by force minimisation

The algorithm is developed such, that it can be used both for the estimation of the DSM and the DTM. As the active surface is only allowed to move up or down the process is simplified to great extend. Both inner and outer forces are introduced.
Inner forces - this kind of forces enable the active surface to react elastically. This property makes it possible, that not every point is touched by the surface. The force is defined as

$$F_D = r \cdot C_D \, . \qquad (1)$$

Where r is the distance to the neighbouring pixel and C_D is a constant value (Figure 2a)

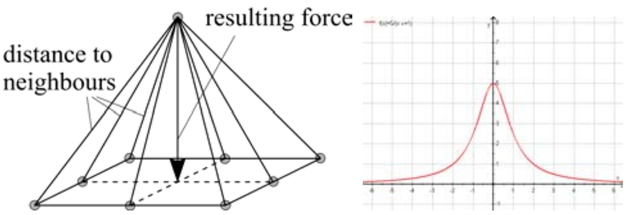

Fig. 2: (a)Inner force (left); (b) Outer force – magnetic force

As a raster point is only allowed to move vertically just the height difference is necessary for the calculation of the distance. The forces to the eight neighbours are summarised resulting in the final elasticity force.

Outer forces - make it possible for the surface to change their form (Figure 2b). The relation between inner and outer forces decide, how strong the resulting deformation of the area will be. Two different forces are used: A constant pressure force is pressing each pixel with the same strength upwards. The magnetic force is the second one, which additionally influence the pixels of the active surface. This force increase in case the distance is reduced. Therefore, nearby raw data points can attract the active contour surface, while points with a large distance almost have no influence.
The magnetic force is calculated as following:

$$F_{Mag} = \frac{K}{r^2 + C} \qquad (2)$$

where K represents power, C stands for K/F_{max}, F_{max} is the maximal magnetic power and finally r represents the distance between raw laser points (punch area) and the active surface.
As an example the process of the DTM generation is presented in detail:
- The active contour surface is filled with the same values as the punch area. In the beginning the inner forces are very strong, as the surface has a very rough shape, therefore the changes in the iteration process are large. In this step no error extraction is allowed, as nearly the whole area would be classified as errors.
- In the first iteration process, the magnetic force is restricted, in order to prevent that the active surface can separate itself from points which are too high. After a few iterations the surface is almost static. Now an error search is following. Thereafter the iteration process is continued until the surface changes no longer.
- In the following step the magnetic force and the maximal magnetic force have to be decreased and the minimisation process starts again until a balance is reached.
- Finally all raster points touching the punch area are fixed, while all other points can move without the influence of outer forces into a position with minimal energy. The process is finished, when no more movements occur, e.g. less than 0.1mm per iteration.

2.2 Single Tree Delineation

In the smoothed DSM tree tops are detected using a local maximum filter. A pixel counts as a local maximum, if all of its neighbours have got a lower height-value or if all neighbours of some connected pixels with equal height have got a lower height-value. Starting from the local maxima, a pouring algorithm is detecting the approximate tree border (Fig. 3). This method resembles water being poured onto mountains, thus being similar to an inverted watershed-algorithm (Soille, 1999).

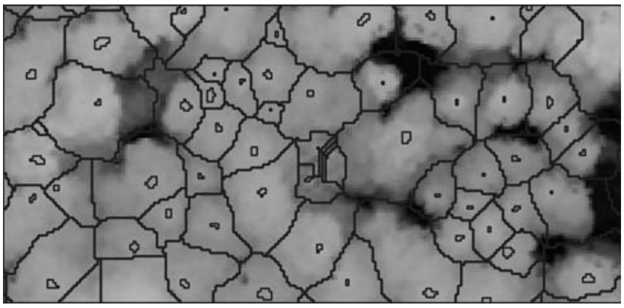

Fig 3: Result of the pouring algorithm

Still a lot of wrong segments exist: Regions are too small to be a tree, some have got shapes that are improbable to belong to a tree, some have unusual spatial relationships to each other and others cover a tree as well as a neighbouring canopy-gap.
Following steps are done in order to improve the segmentation result. To adjust the thresholds for the ensuing steps according to the height of each tree, the crown-regions are firstly split into two parts, depending on the height of their tree-top. Trees over 22m are from now on be referred to as “high trees”, below 22m as “low trees”.
Trees have got a certain, height dependent minimal area. High trees with an area below 3 m² and low trees with an area below

1 m² are selected. For each of those regions the neighbour with the longest common border is selected and is merged with the original region (Fig. 4a). The higher top of both trees becomes the top of the new tree.

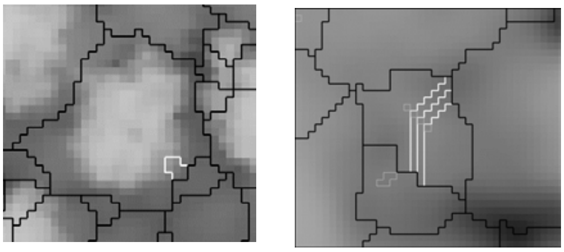

Figure 4: (a) Very small segments (white) are merged with the neighbour with the longest common border; (b): Merged trees as the distance between tops is too short

Furthermore tree tops have got a certain minimal distance from each other. For low trees 1m and for high trees 2m are chosen. If two tree tops are within this distance, the corresponding crown-segments are merged (Fig.4b).
There still exist groups of trees that could not be separated. Elliptical groups are identified with a combination of a minimal area and the regions' anisometry. If a region has got a length of at least 2.5 times its width and has got at least three times the respective minimal area for its height class, it is marked as a group. Those congregations are disjoined analogous to (Straub and Heipke's (2001) approach, which has been developed for tree groups within settlements (Fig. 5).

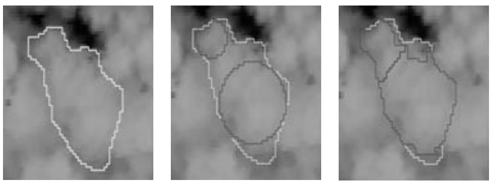

Fig. 5: For each tree group the biggest inner circle is detected and subtracted from this region. Thereafter the biggest identified inner circle of the remaining region is subtracted and so on, until the circle's area falls below the double minimal area for the height class.

Subsequently, the circles are expanded as long as there are no height differences above 60cm between the new and the old border pixels, until the new regions touch each other or the border of the original group is reached.
Finally the actual crown edge is determined to separate a tree from neighbouring canopy gaps or from adjacent understorey trees. Friedlaender's (2002) idea of detecting tree crowns along search rays is only used to determine the final crown edge by reducing the tree shape based on the previous segmentation results (Fig. 6).

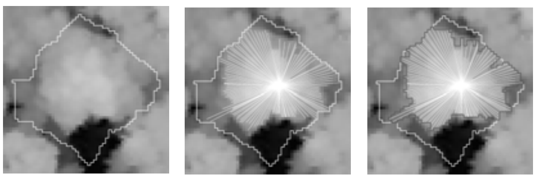

Fig. 6: Ray algorithm used for the calculation of reduced border lines of the delineated trees.

Starting from the tree top, a ray to each border point has been calculated. Proceeding in one pixel wide steps on each ray, the slope of the tree crown at each of these vector points is estimated and generating a boarder point, if the gradient exceeds 2.5m per 0.5m distance (Diedershagen, 2003).

2.3 Tree species classification and modelling

Two methods have been developed used for tree classification. The first is a statistical one based on linear stepwise discriminant analysis and the second one is a form fitting algorithm, where an extended superquadric (ESQ) is used to fit trees either based on raw laser data or based on the DSM.

2.3.1 Single tree classification by discriminant analysis

Three different groups of trees are separated, young and old deciduous trees and conifers. The classification of the delineated trees is done by linear stepwise discriminant analysis. A bundle of form parameters and additionally three simple colour indices are defined as input for the analyses. Three types of form parameters are introduced, representing a) the form of the crown border (e.g. anisometrie, bulkness, circularity etc.), b) the complete 3D-form (e.g. ratio of light-crown-length and crown-radius, ratio of light-crown-length and tree-height) and c) the roughness of the crown surface (e.g. entropy). The following colour indices have been applied, the ratio-vegetation-index (RVI), the ratio-green-vegetation index (RVIg) and the normalized difference vegetation index (NDVI) (Hildebrandt 1996). Also the multi-spectral data (4 channels: R, G, B, NIR) used were recorded with the TopoSys digital line camera.
As a criteria for the quality of the analysis the Wilks lambda was employed. Unfortunately almost none pine and fir are found in the test areas. Three tests have been done, one where only form parameters are used, a second one only introducing multi-spectral parameters and a combined version, where all 21 parameters have been introduced (Heyder 2003).

2.3.2 Modelling based on extended superquadrics (ESQ)

Several authors, e.g. Pollock 1996, Gong 2002, Straub 2003, Vögtle 2004, modelled trees by a generalized ellipsoid of revolution (**GER**) in order to decide whether an object is a tree or not, and/or to model the shape of a tree. Taken this model the authors assume, that a tree has a circular base and that the top of the tree is lying perpendicular above the centre of the base. This model is valuable to decide, whether an object is a tree or not, but if a tree has to be classified as deciduous tree or conifer or if it is intended to estimate the volume and shape of the light crown of a tree, a more complex model could show better results.
This is the reason, why the geometric model of an extended superquadric (ESQ) has been introduced. The mathematical formulation of a superquadric (SQ) is given by equation (3) and an impression of its flexibility is shown in Figure 7.

$$\left[\left(\frac{x}{a1}\right)^{\frac{2}{e2}}+\left(\frac{y}{a2}\right)^{\frac{2}{e2}}\right]^{\frac{e2}{e1}}+\left(\frac{z}{a3}\right)^{\frac{2}{e1}}-1=f(x,y,z) \quad (3)$$

Equation 3: Implicit mathematical expression of a superquadric. The parameters stand for: a1 = radius in x; a2 = radius in y; a3 = radius in z; e1 = curvature perpendicular to xy-plane; e2 = curvature for the plane parallel to the xy-plane.

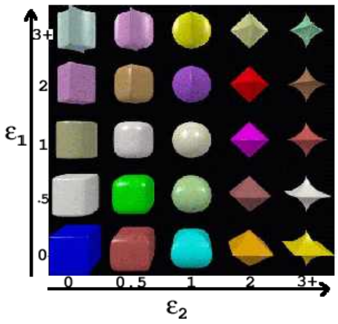

Fig. 7: Changes in the shape of a SQ only caused by the variation of the parameters e1 and e2 (Chevalier, L 2003).

Still this geometric model is quite a restricted one. As trees are normally not symmetric in shape, the following deformations have been integrated to the model (Jaklic, A., 2000):
Tapering (kx, ky) – this geometric constrain causes a dilation or compression along one direction (Fig. 8b).
Displacement (vx,vy) – all planes parallel to a distinct plane will be displaced by different amounts in order to achieve a kind of displacement of the SQ. The z-coordinate is not, but the total height is changed (Fig. 8c).
Bending (kb, ab) – cause a curvature of a straight axis of the SQ. The length of the axis is not changed, but the planes are rotated by different angles. This is the difference to the displacement and to the torsion (Fig.8d).
Cavity (kc) – introducing this deformation a convex object can be changed to concave one (Fig.8e).
Torsion (kt) – cause a torsion around the z-axis (Fig. 8f)

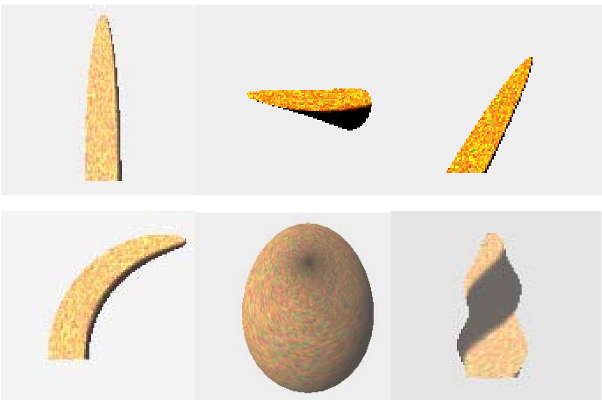

Fig. 8: Upper half of a ESQ without and with deformations is shown (From left to right, from up to down): a) original b) tapering, c) displacement, d) bending, e) cavity, f) torsion

Finally the following function has to be minimised

$$\Phi = \sqrt{a1 * a2 * a3} * F^{el} - 1 \qquad (4)$$

with
$F^{el}(x,y,z,a1,a2,a3,e1,e2,\phi,\theta,\psi,px,py,pz,kx,ky,vx,vy,kb,ab,kt)$,

where (x,y,z) represent the coordinates of a laser point, (a1, a2, a3, e1, e2) are the 5 parameters of the original SQ. With the help of the six parameters ϕ, θ, ψ, px, py, pz the local coordinates of the ESQ are transformed into a world coordinate system. Finally the following parameters (kx, ky), (vx, vy), (kb, ab), kc, kt realising the global deformations.

The fitting process has been implemented in such a way, that all parameters can be introduced separately as stochastic. Furthermore robust fitting and a priori weights for each laser point are possible. Finally additional geometric constraints are used, to be able to fit also the more simple model of GER or even a sphere with the method presented here. Thus the algorithm is very flexible and all possible parameter combinations can be tested to find the one, with which good results are reachable.

3. RESULTS

Some results achieved by the methods presented above using the data from the two test areas Mooswald and Günterstal are presented in the follwing chapter.

3.1 DSM/DTM

Unfortunately no large reference areas are available, therefore no detailed tests could be done. It is only possible to compare the DSM/DTM's calculated with the active contour algorithm (ACA) with those delivered from TopoSys and compare both visually with the raw data. Of advantage have been the good knowledge of place, so that especially critical areas are known and at least a tendential conclusion can be done. The DTM's calculated by the ACA are closer to the real terrain represented by the raw data, as the TopoSys DTM. Concerning the DSM calculation, it can be accentuated, that the DSM's calculated by TopoSys are smoother as the one based on ACA, which are fitted tendentially nearer to the raw data and therefore showing a slightly rougher surface. This is correct, but can cause problems for object extraction and classification.
In order to be able to do secure statements, it is necessary to get lidar as well as reference data from one or more test areas. A cooperation started with the Bavarian National Park Administration can solve this handicap.
Some problems appeared especially in the DTM calculation. Problems occur with large flat buildings, as they are sometimes interpreted as terrain. Also very steep terrain edges, covered by vegetation, are not always modelled correctly. Furthermore, if the pixel size is not chosen in an appropriate manner, sags can occur in the active contour.
Predefined parameter sets for different terrain situations have been designed, so that the inexperienced user can choose the adequate parameter set to solve the task. For the DSM calculation following sets are prepared: exact, exact-error, smooth, with- and without power supplies. E.g. "exact" means, that always the highest value falling into a pixel of the active contour is used. In case of "exact-error" existing outliers are deleted. In forest areas trees and not the variations within a tree are of interest, therefore a smoothing mechanism has been considered in the DSM calculation. For this purpose the "smooth" parameter set is designed. Corresponding models also exist for the DTM calculation.

3.2 Single tree extraction, classification and modelling

3.2.1 Single tree extraction

A comparison of the segmentation outcome with the reference trees is shown in table 1.
Of the 49 douglas firs measured terrestrially, 47 automatically detected trees are found. 87.3 % of them are identified correctly or at least satisfactory. Mainly some very small trees are omitted. Crown areas are overestimated: the mean crown area of the reference trees is 8.2m², compared to 11m² of the segmented trees. Corresponding to the 49 broad-leaved

reference trees only 30 automatically delineated trees are found. Of those, 50 % are delineated well or satisfactory, 43.3 % include several merged reference trees.

Table 1:

Plot	No. of trees	Cor-rect		Satis-Fac-tory		merged		split		Not detec-ted	
Comp. to			in %		in %		in %		in %		in %
Terres-trial											
Doug-las fir	47	28	60	13	28	1	2.1	0	0	5	11
Deci-duous trees	30	6	20	9	30	13	43.	2	6.7	0	0
Phot-gram-metric											
Mixed forest	457	207	45.	75	16	117	26	19	4	39	8
Total	534	241	45	97	18	131	24	21	4	44	8

The merged trees combine partly subdominant trees with an adjacent dominant tree. Partly dominant trees which build a dense, homogeneous canopy could not be separated. Compared to the photogrammetrically measured reference crowns, 61.7 % of the trees are delineated correct or satisfactory, 25.6 % merge two or more reference trees, and 4.2 % are split. 39 reference trees (8.5 %) have not been detected.
The segmentation results are very encouraging for coniferous species. Almost all dominant trees are found and the crown delineation is very close to terrestrially measured crowns. Compared to the terrestrially measured crown polygon, the crown's edge is sometimes even more precise, although the crown area is overestimated. For deciduous species the segmentation severely underestimates the tree number, many reference trees are merged. This is partly due to not registered subdominant trees, but also some dominant tree crowns are merged. Especially densely growing hornbeams with a homogeneous height-distribution could not be separated. However, if the crowns of dominant trees are growing apart from each other, if the trees stand isolated within a canopy gap or if the crowns are more or less hemispherically shaped, the segmentation outcome is good for deciduous trees as well. Possibly a more sophisticated adaptation of the filter intensity to the canopy conditions will improve the segmentation.

3.2.2 Single tree classification by discriminant analysis

Three different groups of trees are introduced, young and old deciduous trees and conifers.
The form and colour parameters have been calculated for 16001 trees. From these trees 13.3% are used for the creation of the discriminat functions and from further 31.7% the group membership is known. With the last mentioned the quality of the results of the discriminant analysis is checked.
Following form parameters (listed in the order of their importance) circularity, ratio of light-crown-length to crown radius and the entropy are the most important ones in the analysis. These three parameters represent a Wilks Lambda of 0,561 and thereby already explain more than the half of the dispersions between the three introduced tree groups.
Almost 80% of the deciduous trees have been classified correctly only based on the form parameters. On the other hand just 64% of the conifers are correctly classified. About 30% of them are classified as "young" deciduous trees. This effect is explainable as young deciduous trees have a similar shape as conifers.
In the discriminant analysis, where also the colour information has been used additionally, the RVI parameter has been placed as fourth variable by the algorithm. This means it is quite important. The other two colour parameters do not prevent more information for the analysis. Using both types of information the percentage of correctly classified conifers increase to 69%, whereas the classification result of the deciduous tree classes remained nearly unchanged.

3.2.3 Tree modelling and classification based on ESQ

Based on the ESQ, first tests have been done to model the delineated trees using the raw laser data. As mentioned, also the GER used by several authors is tested with the developed program. Parameter e1 corresponds to n ($e1 = 2/n$).
It shows, that especially the fitted e1 value is to a great extend dependent on the chosen start value. This conclusion is valid both for the GER and if all parameters are used as stochastic variables.
Therefore the following two step procedure is used with success:
a) First use the estimated radii a1, a2 calculated by a linear ellipse fit and the radius a3, calculated as the difference of the highest raw data point and the mean of the height values of the tree border pixels. Only e1 and the global deformations are stochastic.
b) Choose the estimated value of parameter e1 as start value and let also the radii a1, a2 , a3 be stochastic with restricted limits of variations.
The following parameters should not be variable. The two global rotations θ, ψ; the parameter pz, as it is highly correlated to a3, and curvature e2. Still the flexibility of this method prevent a superior geometric model compared to the one fitted by GER.
Tree volume should only be calculated for the upper part of the ESQ, representing the light-crown of the tree, as no information of the lower part of the crown is given.

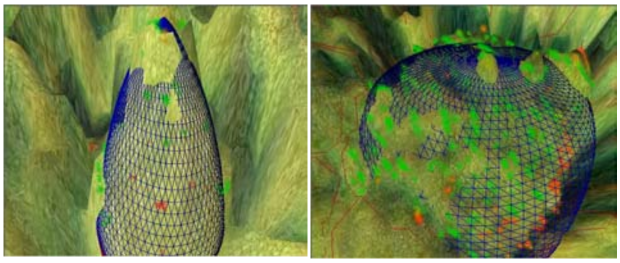

Figure 9: (a) A conifer and (b) a deciduous tree fitted by a ESQ

Implementation is done carefully. The sqrt-minimum restriction of the product of the a1,a2,a3 radii (see equation 4) should be integrated, as otherwise unpredictable local minima can be found, which probably cause the affects mentioned in (Vögtle 2004).
Furthermore robust outlier detection based on the Huber distance is used. Figure 9 shows a conifer and a deciduous tree fitted by ESQ. It seems that modelling based on ESQ's result in tree shapes, which fit better to the used data, compared to modelling with GER. Thereby a more reliable classification can hopefully be achieved. This conclusion has to be proven in a more comprehensive test.

4. CONCLUSIONS

Concerning DSM/DTM filtering, more investigations have to be done, especially to try to detect edges and ridges in advance in order to integrate this information into the calculation process to achieve more precise and reliable DTM's. Furthermore buildings should already be detected with the help of the calculated DSM, so that these areas can be masked before the DTM calculation.

Tree delineation, classification - The number and position of most trees is found in these test areas, but crown areas are slightly overestimated. Problems manly occur with detecting very small or suppressed trees. It is difficult to separate tree crowns from each other, in dense deciduous forests with a closed, homogeneous canopy. Thus, the stem number is underestimated. Stem counts in such stands might be improved by advanced lidar technology like the full-wave system appeared at the market this year. One of the most important tasks is to improve the delineation algorithm, as it is the base for the derivation of all interesting data concerning single trees.

Modelling – the ESQ model is flexible such, that a wide range of objects can be fitted and it is still possible to geometrically interpret the estimated parameters.

The methods presented have reached a level, where it is allowed to argue, that they can be used with some corrections and extensions as a fundament for a semi-automatic inventory system based on both lidar and multi-spectral data. In our opinion lidar data will play an important role for small scale forest inventories, especially for deriving tree heights and stand volume in the near future.

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