FOREST PARAMETER DERIVIATION FROM DTM/DSM GENERATED FROM LIDAR AND DIGITAL MODULAR CAMERA (DMC)

M. Heurich[a]* S. Schadeck[b], H. Weinacker[c] ,P. Krzystek[b]

[a]Bavarian Forest National Park, Department of Research - marco.heurich@fonpv-bay.bayern.de
[b]Munich University of Applied Sciences, Department of Geoinformatics - krzystek@geo.fhm.edu
[c]Freiburg University, Department of Remote Sensing and Landscape Information Systems – holger.weinacker@felis.uni-freiburg.de

KEY WORDS: Forestry, DEM/DTM, Laser Scanner, Digital Imagery, Individual Tree Detection

ABSTRACT:

Ecological analysis and forest planning need sophisticated information about the structures of forests. In recent years new sensor systems like laserscanner and digital airborne cameras emerged on the marked which fulfil the high requirements for forest applications. Also, new methods for automated delineation and feature extraction of individual trees have been developed. In this study images of the brand-new Digital Modular Camera were used to automatically generate a DSM by image matching techniques. The resulting density of matched 3D points was 18 pts/m^2. After the robust filtering the cleaned point cloud showed a mean density of 11 pts/m^2. The photogrammetric DSM was subsequently compared to a manual stereoscopic measurements and ground surveys. Tree height measurements from stereoscopic measurements showed a better accuracy than heights derived from laserscanning DSM and the photogrammetric DSM. The applied method of DSM generation using a feature-based matching approach could successfully reconstruct deciduous canopy surfaces with almost the same accuracy as the laser scanner did. However, the method failed especially when single coniferous trees were present in the plot by cutting the tree tops and underestimating the lower areas between the trees. Several ways to improve the matching strategy of the present algorithm for canopy reconstruction are discussed. The potential of the photogrammetric and laserscanner DSM`s for automated tree detection could be clearly shown by applying a single tree delineation algorithm which is based on a watershed approach.

1. INTRODUCTION

For decades humans have been manually interpreting aerial photographs of forests: counting stems, classifying species and stands. Also tree heights were estimated using stereoscopic aerial photographs. Because of its importance to forest inventory early studies examined the crown surface with photogrammetric methods (Hildebrand et al. 1974).
Since the conventional methods are pretty time intensive only stand delineation's are performed with the help of aerial photographs in central Europe. Forest assessment on a single tree level is done by field based sampling of trees. For a wider use of remote sensing in forest inventory new cost effective methods have to be developed. Automated individual tree crown mapping (delineation and feature extraction) is a main focus of forest inventory research. Accurately mapped and classified crowns are useful to attain several management goals (e.g. volume calculations or habitat modelling). The following two preconditions appear mandatory.
Firstly, sensors with high spatial and spectral resolution are needed which render possible the characterisation of forest structures like canopy surfaces or the detection of single trees. Some of the new sensors which emerged in the last years fulfil these preconditions to a large extent. Laserscanning is a technology with great potential for applications in forestry. Since laser beams partly penetrate the forest surface Digital Surface Models (DSM) and Digital Terrain Models (DTM) can be generated by suitable filter techniques. Depending on the measuring density of the laserscanner it is possible to achieve a spatial resolution of less than half a meter. Also, the new digital airborne cameras like the DMC (Z/I-Imaging), ADC (Leica-Geosystems) or the HRSC-A (DLR) provide high resolution panchromatic and multispectral imagery which can be used to automatically extract 3D objects and their characteristics. GSD's of 10 cm or less are possible mainly depending on the image scale. For instance, Hese at al. (2000) report about the generation of DSM in forest areas from HRSC-A imagery with a post spacing of 1m at a GSD of 12cm. Although spaceborne optical sensors are reaching meanwhile a half meter resolution and airborne radar sensors (InSAR) are getting under the 1m level, these sensors cannot contribute so far to a detailed analysis of forest structures on a tree level due to their limited DSM resolution they can provide.
Secondly, the increase in resolution implies a paradigm change in techniques of digital image analysis, since algorithms developed for coarse resolutions are not directly applicable to high resolution imagery. Therefore, new methodologies for automatic detection of trees have been developed in the recent years. There exists several approaches like segmentation (Gougeon 1999), finding local maxima (Dralle 1997), edge detection techniques (Brandberg and Walter 1999) and watershed approaches (Person et al. 2003).
In this study images of the brand-new Digital Modular-Camera (DMC) were used to automatically generate a DSM by image matching techniques. The photogrammetric DSM was subsequently compared to a laserscanning DSM, manual stereoscopic measurements and ground surveys. The potential of the photogrammetric DSM´s for automated tree detection could be clearly shown by delineation of single trees using a method developed by the University of Freiburg. This research is embedded in the research project "Evaluation of remote sensing based methods for the identification of forest structures", which has been established to investigate different airborne sensors like laserscanner, InSAR and digital cameras in

combination with different analysis methodologies for the automatic detection of forest attributes (Heurich et al., 2003).

2. MATERIAL

2.1 Study Area

The research was conducted in the Bavarian Forest National Park which is located in south-eastern Germany along the border to the Czech Republic (49° 3' 19" N, 13° 12' 9"E). Within the park three major forest types exist: There are sub alpine spruce forests with Norway spruce (Picea abies) and partly Mountain ash (Sorbus aucuparia) above 1100m. Mixed mountain. forests with Norway spruce, White fir (Abies alba), European beech (Fagus sylvatica) and Sycamore maple (Acer pseudoplatanus) can be found on the slopes between 600 and 1100 m Finally, spruce forests with Norway spruce, Mountain ash and birches (Betula pendula, Betula pubescens) occur in valley bottoms with wet depressions often evidencing cold air ponds.

2.2 Field Data

Three sample plots with a size between 20 by 50m and 20 by 100m were selected in the sub alpine spruce and mountain mixed forest zones. The field data was collected in May and September 2003. Several tree parameters like the diameter at breast height, total tree height and starting point of crown were determined for each tree being higher than 5m. The height measurements were carried out with the "Vertex" III system following the definitions of Kramer and Akca (1995). Each stem position was precisely measured by tachometry and DGPS. The absolute accuracy was comprehensively checked and was estimated to 1-2 cm. The data was subsequently evaluated and visualised with the help of the program package SILVA 2.2, which is commonly used for forest simulations (Pretzsch et al. 2002). The mean annual growth in height was determined for the stands with 20 to 25 cm. Plot Hochwiesel A (50) is a typical natural Norway Spruce stand of a subalpine environment. Its average height above see level is 1240 m. Feistenhäng A (60) is a pure deciduous tree stand dominated by European beech. It is located in the mountain mixed forest zone 890m above sea level. The size of the plot is 20 by 50m and the slope is 15.3%. Plot Lärchenberg B (22) is an old growth stand typical for the mountain mixed forest zone with European beach, Norway spruce and Sycamore maple located 885m above sea level. The size of the plot is 20 by 100 and the slope is 29.8%.

plot	Spe-cies	N/ha	h100 [m]	d100 [cm]	G [m³/ha]	V [m³/ha]	D°	%
22	Picea	45	41.7	77.4	21	349	0.31	30
	Fagus	165	29.5	37.7	13	189	0.46	44
	Acer/Tilia	40	28.7	52.5	9	130	0.28	27
		250			43	668	1.05	
50	Picea	225	26.5	60.6	42	472	1.0	100
60	Fagus	260	34.1	53.1	28	470	0.88	91
	Acer	20	26.1	38.7	2	32	0.08	9
		280			30	502	0.97	

Table 1: Forest characteristics of the sample plots (N/ha: number of trees per ha, h100: dominant height (average height of the 100 tallest trees), d100: dominant diameter, G: basal area, V: growing stock, D°: stock density).

2.3 Aerial Data

2.3.1 Digital Modular Camera (DMC): The DMC flights were performed in end of June 2003 in four separated blocks The flying height was 960m resulting in a photo scale of 1:9.000 and a GSD of 11 cm. The images were captured with 70% end lap and 50% sidelap covering the area of interests in two neighbouring strips. Z/I-Imaging provided the images with a size of 13824 x 7680 pixels in CIR colour mode. The georeferencing of the blocks was achieved by processing solely DGPS and INS data with POSEO and subsequently applying an automatic aerial triangulation with ISAT. No ground control points were used initially. The stereo models were perfectly free of y-parallaxes indicating an internal consistent block geometry. The DMC is one the first operational digital aerial cameras. It uses a modular design based on several overlapping CCD frame cameras. It provides both panchromatic and mulitspectral images (Hinz et al., 2001).

2.3.2 Laser Scanner: There were two flights with the "Falcon" airborne laser scanner system from TopSys Topografische Systemdaten GmbH. The first flight was in spring after snowmelt but prior foliation. The second flight took place in summer 2002. The average point density was 5pts/m² in the spring flight and 10pts/m² in the summer flight. First and last pulse data was collected during both flights. The TopoSys System is based on two separate glas fibre arrays of 127 fibres each. Its specific design produces a push-broom measurement pattern on ground. For further details see Wehr and Lohr (1999).

Sensor type	Pulsed fibre scanner
Wave length	1560 nm
Pulse length	5 nsec
Scan rate	653 Hz
Pulse repetition rate	83.000 Hz
Scan with	14.3°
Data recording	first and last pulse
Flight height	800 m
Size of footprint	0.8 cm

Table 2: System parameters during the Laser Scanner flight

3. METHODS

3.1 Data Preparation

3.1.1 DMC images: After the initial georeferencing just using transformational parameters without any ground control the blocks showed a significant absolute shift of about 50m both in planimetry and height. Thus, a second aerial triangulation was carried out using GCP´s which were photogrammetrically derived from another block being available for this test site (photo scale 1:10000, c = 300 mm). The absolute accuracy of the re-georeferenced DMC blocks determined at several check points was found to be 20cm in planimetry and 1m in height. This is fully consistent with the theoretical expectations for the absolute accuracy of the second block. DSM´s were subsequently calculated with ISAE which is a software package for automatic DTM generation using image correlation. The software takes full advantage of the 12 bit resolution and uses the green channel by default for the image matching. No weighting of the three channel was possible. The approach takes advantage of a feature-based matching technique and a robust DTM filtering based on finite elements. It was originally designed for DTM generation, especially in open areas. Because of the robust statistics the approach is capable of eliminating single small objects like trees if the majority of the matched 3D points is representing the terrain. Also, the original approach is restricted to a stereo pair and a 2.5 DTM. The latter is due to the fact that the DTM is a simple raster allowing just one height value for a planimetric position (Krzystek and Wild 1992). Since it was planned to reconstruct the forest canopy as good as possible a small grid spacing was envisaged. In order to get the sufficient redundancy the point density was maximised by deriving interest points in each epipolar line. The resulting density of matched 3D points was 18 pts/m^2 based on a mean point distance of 11cm across track and 66cm along track. After the robust filtering of the 3D points the cleaned point cloud showed a mean density of 11 pts/m^2 indicating an error percentage of 30%. The grid spacing was set to 1m although 0.5 m might have been better. However, the current version of ISAE did not allow for a smaller grid width. Since the DSM's still showed slight shifts both in planimetry and height if compared to the laserscanning DSM's they were locally co-registered by comparing profiles at single tree crowns. The remaining discrepancies between the DSM's were in the order of 10cm.The absolute height accuracy of a single matched 3D point can be estimated to 11cm by taking into account the side lap, the image scale and a matching precision of 1/3 pixel.

3.1.2 Laser scanner data: The processing of the laserscanner data for each strip was performed in house by TopoSys using a standard procedure called TopPit. The DSM was filtered from the last pulse data by emphasising the highest points of the laserscanner data and eliminating outliers. The DSM contains in this study only height information about vegetation. The DTM was derived from the last pulse data by filtering the vegetation points. The original grid spacing of 0.5m was subsequently resampled to a 1m grid. The georeferencing of the data was achieved by a standard transformation using the parameter set DHDN Süddeutschland. Slight deviations from the local datum were compensated by an adjustment with polygons of buildings derived from the digital cadastral map and with control points measured by GPS. Checks at some control points indicated a positional accuracy of less than 0.5m.

3.2 Data analysis

Profiles were measured manually in the digital stereo workstation SSK from Z/I-Imaging across each stand to compare the two types of DSM's. Only true 3D points which could be clearly identified in both stereo images were measured. The measured points can be grouped into the following classes: tree tops, tree crowns, valleys between trees and ground surface. The manually measured profiles were compared against profiles which were calculated from the lasercanning DSM and the photogrammetric DSM by height interpolation at the same planimetric positions.
A comparison of the tree height captured by the field technique was only carried out if the tree could be clearly identified in the stereo workstation. Tree heights derived from laserscanning DSM, photogrammetric DSM and tree heights measured manually in the stereo workstation were compared to field measurements by interpolation of the stem positions. The data analysis and visualisation was carried out in ARC GIS 8.3.

3.3 Automated individual tree delineation

The individual tree recognition was achieved by a special approach developed at the University of Freiburg. The procedure is based on a rasterised DSM and DTM. The algorithms are implemented using the HALCON image processing software which is a developing system mainly used in the area of machine vision applications. In the first step a digital crown model (DCM) is calculated by subtracting the DTM from the DSM. The DCM is subsequently smoothed by a gaussian filter. The following main step is a pouring algorithm for the estimation of tree tops and crown areas. After the calculation of local maxima an expansion is performed until the valley bottoms are reached. The areas referring to one maxima are considered as single trees. In order to enhance the results additional functions have been introduced to this main concept. For more details see (Diedershagen et al. 2003).

4. RESULTS

4.1 Accuracy of tree height measurements

From the results shown in table 3 the following conclusions can be drawn. The laser scanner underestimated the tree heights about 2m in comparison to the ground measurements. This effect is quite similar for the deciduous and the coniferous stand. It is less evident in the old growth stand, since the ground measurements were performed one growing season earlier. The standard deviation is about 1m in the deciduous and the coniferous stand and 1.3m in the old growth stand. Also the stereo measurements underestimated the tree heights. The amount of this underestimation is about 1m if compared to the laser data. One reason for this is that the DMC flight was performed on year later. However, this contributes only 0.2 to 0.25cm to the total difference. Consequently, the stereo measurements are closer to the tree heights measured with field technique. The standard derivations are almost equal to the corresponding value of the laserscanner data. The image correlation underestimated the tree height, too. In relation to the laser data the underestimation is similar in the deciduous stand, almost 1m larger in the coniferous and even 2.4m larger in the old growth stand. The standard deviation is almost the same for

[m]	ground - laser	ground - stereo	ground - image correl.	stereo - laser	stereo - image correl.
Plot 22 (n=26)					
SD	1.29	1.36	5.37	1.19	5.35
Mean	1.40	0.42	3.78	0.99	3.37
R^2	0.94	0.96	0.37	0.94	0.37
Plot 50 (n=39)					
SD	0.92	0.72	1.77	1.00	1.81
Mean	2.08	0.92	2.99	1.16	2.08
R^2	0.84	0.89	0.36	0.81	0.30
Plot 60 (n=18)					
SD	1.13	1.08	1.08	0.27	0.50
Mean	2.37	1.58	2.10	0.79	0.51
R^2	0.74	0.76	0.75	0.97	0.90

Table 3: Differences of tree heights determined by different methods in meter. Laser: DSM Laser Scanner. Image Correl.: DSM derived by image correlation. Stereo: Stereo measurements. Ground: Tree measurements on ground.

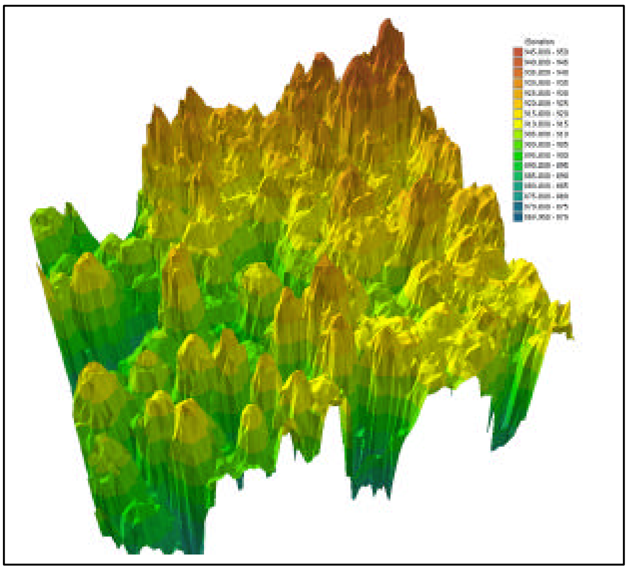

Figure 1: DSM of the old growth stand 22 - laser scanner

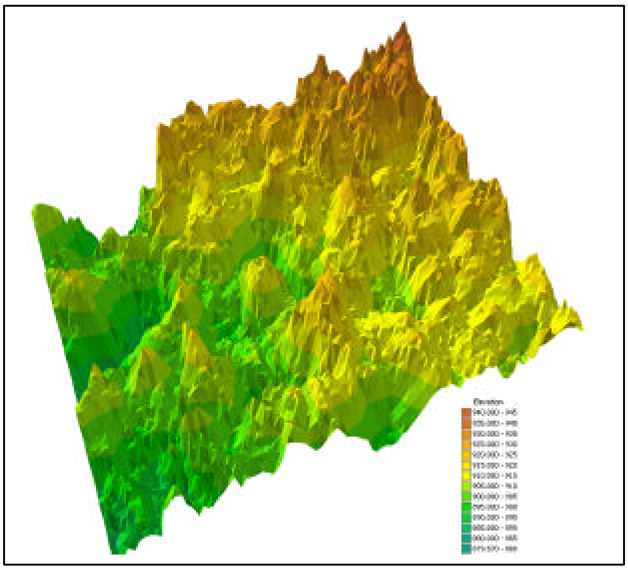

Figure 2: DSM of the old growth stand 22 - DMC

the deciduous stand, about 0.8m larger in the coniferous stand and reaches the high value of 5.37m in the old growth stand. The relationship between ground height and laserscanner height in terms of the correlation coefficient is weaker if compared to other studies (Persson et al., 2003). The reason for this is that the height interpolated at the stem position was taken as the tree height instead of the largest difference between DSM and DTM closest to the stem postion. Most tree tops are not perpendicular to the stem positions, moreover, especially coniferous trees show a conical shape. Therefore, a small shift in planimetry implies a significant height difference and leads - possibly - to coefficients indicating the weaker statistical relationship (Table 3).

4.2 Measuring of profiles

The mean differences in the old growth stand between the stereo measurements and the values of the laser DSM are 0.53m for the deciduous trees and 0.35m for the coniferous trees. This shows that the laser DSM lies beneath the stereo measurements which seems to be reasonable because the DMC flight took place one year after the laser scanner flight. However, the difference is larger than the annual growth of approximately 0.2 to 0.25m. The standard deviations are almost the same and are in the range of 0.8m and 0.9m. When comparing the differences between stereo measurements and image correlation it can be found that the mean value is three times larger than for the laserscanner DSM. This means that the DSM derived by image matching lies far beneath the stereo measurements. The data shows that the mean for the tops of deciduous trees has a similar value than the laser data. The main difference is caused by the mean values of tops of the coniferous trees. In these cases the DSM derived from DMC data is at average 5m beneath the stereo measurements. Figure 5 is showing the reason for this underestimation of coniferous trees in the old growth stand. The tops of large spruce trees which stick out far above the beech trees are cut by the algorithm. The beech trees are cut slightly by the algorithm, too. Also the standard deviations are much larger. They range between 2.34m for the deciduous and 3.83m for the coniferous tops. The mean differences between stereo measurements and laserscanner data in the coniferous stand are larger than in the other stand types. The highest differences are found for the edges of the crowns and the tree tops. However, the ground surface is better determined by

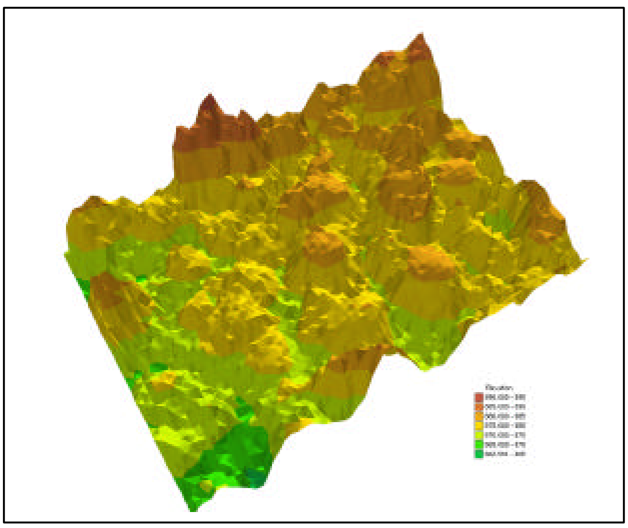

Figure 3: DSM of the deciduous stand 60 - laser scanner

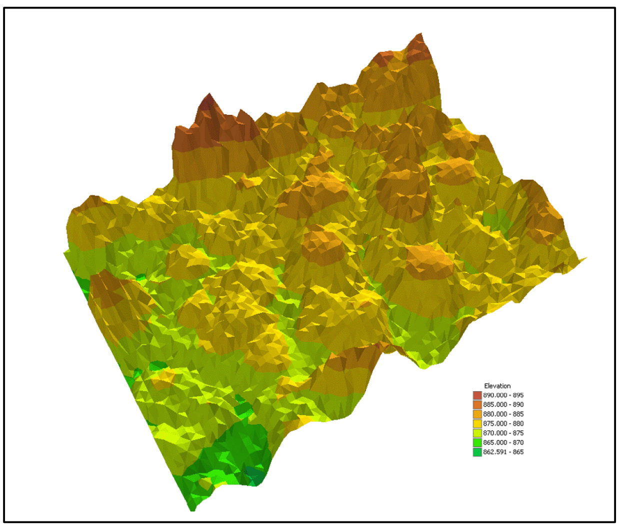

Figure 4: DSM of the deciduous stand 60 - DMC

[m]		stereo - laser	stereo - image correlation	laser - image correlation
Plot 22				
Tops coniferous	SD	0.79	3.83	4.17
n=9	Mean	0.36	5.07	4.71
Crown decid.	SD	0.89	2.34	1.86
n=19	Mean	0.53	0.36	-0.16
Plot 50				
Tops coniferous	SD	1.57	1.18	1.79
n=9	Mean	2.33	2.01	-0.33
Crown conif.	SD	5.79	7.78	7.64
n=16	Mean	3.56	-2.82	-6.38
Regeneration	SD	0.88	1.33	0.86
n=8	Mean	1.83	0.53	-1.30
Ground surface	SD	4.44	7.07	5.94
n=19	Mean	-1.35	-7.67	-6.33
Plot 60				
Tops deciduous	SD	0.55	0.43	0.41
n=17	Mean	0.64	0.17	-0.47
Crown decid.	SD	0.76	0.35	0.63
n=11	Mean	-0.18	-0.10	0.08
Crown edges	SD	0.52	0.42	0.48
n=15	Mean	-0.26	-0.25	0.01

Table 4: Height differences between the DSM´s derived from laser scanner (laser) and image correlation and stereo measurements.

laserscanner data since these measurements are at average 1.35m beneath the stereo measurements. Standard deviations are 0.88m for the regeneration and 1.57m for the tree tops. For the ground surface and edges of the crowns the standard deviation reaches quite high values between 4.44 and 5.79m. The comparison between the stereo measurements and the DSM from the DMC data shows that the stereo measurements are above the data derived by image correlation for the tree tops and the regeneration. The mean values and the standard deviations are comparable to the laser measurements. However, there are huge differences of –2.82 and –7.67m in mean value for the ground surface and for the crowns. Also, the standard deviation reaches very large values with more than 7.0m for these classes. The reasons for this are shown in Figure 5. The DSM derived from the DMC data does not adequately represent the surface structure of the forest. Especially, the valleys between the trees are only poorly rendered. In addition, the tree tops are underestimated. However, this effect is not as significant as in the old growth stand.
Note that the smallest differences between the data types and the lowest standard deviations can be found in the deciduous stand. Comparing the stereo measurements and the laser data the mean value for the tree tops is 0.64m, for the crowns -0.18m and for the edges of the crowns -0.26m. The standard deviations are between 0.52 and 0.76m for the crown edges and crown measurements. The differences between stereo measurements and the DSM derived form DMC data are even smaller. The mean value ranges between -0.25 and 0.17cm for crown edges and tree tops. All standard deviations are less than 0.42m. This data also shows that tree tops are underestimated and valleys between the trees are overestimated by the algorithm.

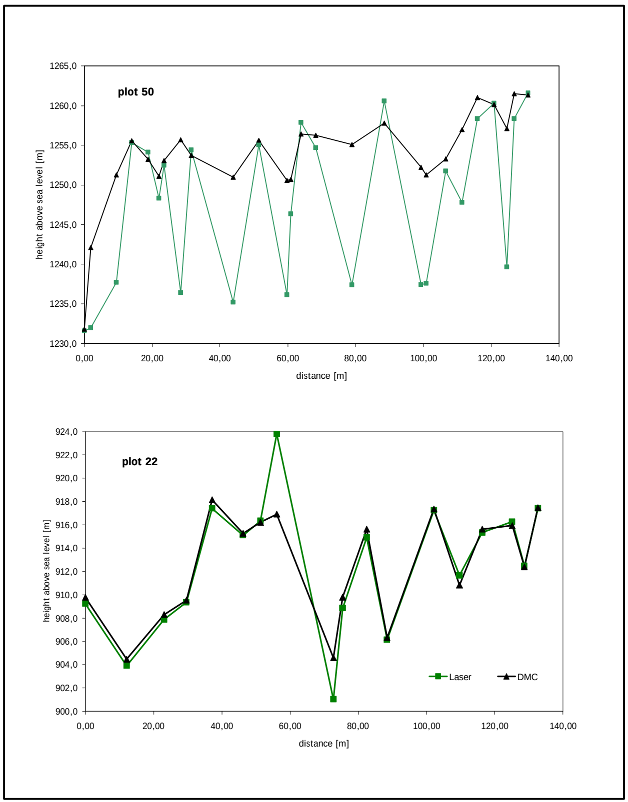

Figure 5: Comparison of the laser scanner DSM and the DSM derived from DMC images at typical vertical profiles through the plots 50 and 22.

4.3 Delineation of individual trees

The results for the automated tree detection depend on the resolution of the grid and on the data source. For the laserscanner data it was possible to calculate a DSM with 0.5 and 1.0m resolution. This led to an increase in detection rate of 16 to 20%. Also the delineation of the crown shape was much more accurate with a resolution of 0.5m. Comparing the results for the spatial resolution of 1.0m achieved by the laserscanner DSM and by the photogrammetric DSM the detection rate for the laserscanner DSM was better than for the photogrammetric DSM for plot 22 and plot 60 while the percentage of detected trees were similar for plot 50. The reason for these results is the relatively large distance between the trees in this plot. Their crowns are separate, the canopy is not closed, so that tree detection is easy even with a 1m DSM which does not render

plot	DSM resolution	data source	detected trees [%] upper layer	middle layer	total
22	0.5	Laser	65.2	17.6	29.6
	1.0	Laser	59.1	6.7	25.0
	1.0	DMC	36.4	5.7	14.9
50	0.5	Laser	86.0	66.7	84.8
	1.0	Laser	65.1	33.3	63.3
	1.0	DMC	67.4	0.0	63.3
60	0.5	Laser	54.8	0.0	37.8
	1.0	Laser	38.7	0.0	26.7
	1.0	DMC	21.9	0.0	15.6

Table 5: Results of the single tree delineation.

the surface perfect. The relatively bad results for the DCM DSM in plot 60 are probably caused by the extend of the DSM. It was probably to small for the tree finding algorithm.

5. DISCUSSION

The results show clearly the potential of DSM generation with high resolution digital cameras for forest surfaces. The point density of matched 3D points of more than 10 pts/m^2 is even better than the TopoSys scanner, which is well known for its high point density.

The applied method of DSM generation using a feature-based matching approach could successfully reconstruct deciduous canopy surfaces with almost the same accuracy as the laser scanner did. However, the method failed especially when single coniferous trees were present in the plot by cutting the tree tops and underestimating the lower areas between the trees. This is mainly caused by the following. Firstly, the matching works erroneously in occlusion areas. Secondly, the single trees representing objects with large x-parallaxes in the images are cut by the algorithm and the matching parameters since no pre-knowledge about the DSM is used. Thirdly, the matching of feature points is error prone since it is restricted to two stereo images. In some cases 30 % and even more mis-matches could be observed which makes robust filtering of a surface almost impossible. However, the procedure was originally designed for DTM generation in open field areas. Therefore, the inferior results especially in the plot 50 are only caused by the specific matching method and the DSM reconstruction which has never been adopted for tree reconstruction.

There are several ways to improve the matching strategy of the present algorithm for canopy reconstruction. Basically the feature-based matching part must take full advantage of multiple image overlap. In our case we would even have a perfect overlap of at least 6 images for the entire area. In this case the error percentage would be drastically reduced because geometrical constraints like epipolar lines could be used. This would in turn lead to a significant improvement of accuracy and reliability thanks to the multiple 3D intersection. Also, the matching part must cope with occlusions which are always present when perspective images of tall objects are used. Furthermore, the simple 2.5 DSM model must be replaced by a true 3D DSM representation based on a TIN structure. If pre-knowledge about the terrain (e.g. laser DSM) is available the algorithm must be able to use it. This approach would use a true 3D DSM representation to model the trees rather than a specific tree model. The latter would also be possible once the single trees are successfully delineated and located by an appropriate method. Since the point density is mainly dependent on the image scale a grid spacing of 50cm or even better is possible.

These results show the potential of DSM´s derived from digital images for forestry and other environmental applications in forested landscapes. In comparison to laserscannning the application of digital cameras shows two main advantages: Firstly, the costs for the image acquisition are much lower. Secondly, spectral information of high quality is collected simultaneously. However, it is not possible to collect information about the vertical structure and the ground surface of forests. Therefore it is to be concluded that for future forest inventory tasks a combination of both sensors is advantageous and promising.

6. REFERENCES

Brandberg T., Walter F. 1999. An Algorithm for Delineation of Individual Tree Crowns in High Spatial Resolution Aerial Images using Curved Edge Segments at Multiple Scales. Proceedings of Automated Interpretation of High Spatial Resolution Digital Imagery for Forestry Proceedings of Automated Interpretation of High Spatial Resolution Digital Imagery for Forestry. British Columbia, Canada. .(eds. Hill, D.A.and Leckie, D. G.) Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre. Pp. 41-54.

Diedershagen O., Koch B., Weinacker H., Schütt C. 2003. Combining Lidar- and Gis Data for the extraction of forest inventory parameters. In: Hyyppä, Naesset, Olsson, Pahlen and Reese, (eds.)Proceedings of the Scandlaser Scientific Workshop on Airborne Laser Scanning of Forests. pp. 156-164.

Dralle K. 1997. Locating Trees by Digital Image Processing of Aerial Photos. PhD thesis. Royal Veterinary and Agricultural University. Frederiksberg. Denmark.

Gougeon F. A. 1999. Automatic Individual Tree Crown Delineation Using a Valley-following Algorithm and a Rule-Based System. Proceedings of Automated Interpretation of Hight Spatial Rsolution Digital Imagery for Forestry Victoria, British Columbia, Canada.(eds. Hill, D.A.and Leckie, D. G.) Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre. Pp. 11-23.

Hinz A., Dörstel C., Heier H. 2001. DMC - The digital sensor technology of Z/I-Imaging. Photogrammetric week 2001. Wichmann Verlag. Heidelberg. pp. 93-103.

Hese S., Lehmann F. 2000. Comparison of Digital Stand Surface Models of HRSC-A and Laser Scanner for Forest Stand Characteristics. IASPRS. Vol. XXXIII. Amsterdam 2000.

Heurich M., Schneider T., Kennel E. 2003. Laser Scanning for Identification of Forest Structures in the Bavarian Forest National Park. In: Hyyppä, Naesset, Olsson, Pahlen and Reese (eds.) Proceedings of the Scandlaser Scientific Workshop on Airborne Laser Scanning of Forests. S. 97-106.

Hildebrand G., Akca A., Djawadi K. 1974. Characterization of the detailed roughness of natural surfaces by a digital surface model. Proceedings: Symposium of Remote Sensing and Photointerpretation. Banff. Alberta. Canada. 2: 755-765.

Krzystek P,. Wild D,. 1992. Experimental Accuracy Analysis of Automatically Measured Digital Terrain Models. Robust Computer Vision – Quality of Vision Algorithms. Wichmann Verlag. Karlsruhe. pp. 371-390.

Wehr, A. and Lohr, U., 1999. Airborne laser scanning – an introduction and overview. ISPRS Journal of Photogrammetry and Remote sensing 54, 68-82.

Pretzsch H., Biber P., Durský J. 2002. The single tree-based stand Simulator SILVA: construction. application and evaluation. Forest Ecology and Management. 162 (2002).

Persson A., Holmgren J., Södermann U. 2002. Detecting and Measuring Individual Trees using an Airborne Laser Scanner. hotogrammetric Engineering & Remote Sensing. Vol. 68. No. 9. September 2002. pp. 925-932.