FILTERING OF LASER SCANNING DATA IN FOREST AREAS USING FINITE ELEMENTS

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ABSTRACT:

During the last decade laser scanning turned out to be one of the most promising techniques in photogrammetry. Some photogrammetrists even say that laser scanning has caused a paradigm change in photogrammetry because of its big impact on methods like DTM generation or 3D city model reconstruction. Originally, laser scanning was designed for DTM generation in forest areas. For that purpose several filtering approaches had been proposed and partly realized in commercial systems. This paper describes another alternative for filtering of laser scanning data. It combines a pre-filter based on a convex hull and a subsequent finite element adjustment. The pre-filter creates a crude TIN DTM assuming that the lowest measured laser points are representing the terrain accurately enough. The following adjustment of this TIN utilizes all laser points except non-ground points. This leads to a slight height change of the TIN points according to statistical and geometrical constraints and to a better approximation of the terrain. The method works hierarchically in a data pyramid starting from a coarse point density of about 4 m. The preliminary system has been successfully applied to laser scanning data that have been captured by the TopoSys system in a test site located in the National Park Bavarian Forest. The results show clearly that the method is successfully applicable in forests areas with different forest structures. The accuracy derived in controlled tests lies in the range of 15 – 25 cm and is also equivalent to the DTM quality of standard filtering procedures.

1. INTRODUCTION

1.1 General remarks

During the last ten years laser scanning has gained the reputation as an excellent and efficient technique for generation of digital terrain models (DTM). Although being intentionally designed for cost effective DTM generation in forest areas, the technique has opened new application fields like corridor mapping of electrical power lines (Ackermann, 1999; Baltsavias, 1999; Maas, 2001; Wehr et al., 1999).

Research work focuses on two major fields.

(1) Theoretical and practical investigations of systematic errors of laser scanning DSMs which are caused by the integrated GPS/INS system and insufficient system calibration (Huising et al., 1998; Kilian et al., 1996; Schenk, 2001; Schenk et al., 2001).

(2) The development of filter techniques for the classification of laser scanning data with respect to terrain points, vegetation points and man-made objects like houses. Furthermore, some research teams are working on integrated approaches to semi-automatically or even automatically extract digital 3D city models from very dense laser scanning data and image data (Brenner et al., 2000; Brenner, 2001).

The filtering techniques comprise morphological approaches (Hug et al., 1997; Kilian et al., 1996; Vosselman, 2000), auto-regressive processes (Lindenberger, 1993), techniques based on a convex hull (Hansen et al., 1999) or the well-known least squares interpolation (Krauss, 2000). Another approach refines adaptively a TIN DTM by using geometrical values like distances and angles as filter criteria (Axelson, 2000). Recently, experiences were reported about a gridding technique that creates hierarchically a raster DTM in a data pyramid by using a height gradient (Wack et al., 2002).

1.2 Filtering techniques for laser scanning data

1.2.1 Morphological filtering

The key idea of this approach is to use the mathematical morphological operators “erosion” and “dilatation” for the classification of laser scanning data (Kilian et al., 1996). A special kernel function is used assuming a locally flat area and by taking into account the terrain slope. Sometimes this filter is used as a pre-processing module in a subsequent filtering process (Vosselman et al., 2001).

1.2.2 Convex hull

This technique works only with geometrical constraints and assumes that the lowest laser scanning points are representing to a large extent the terrain surface. In a first step a convex hull is created for the entire point cloud. Additional laser points, which lie within a user controlled distance bound to the DTM iteratively, refine the first coarse DTM. This technique uses no statistical description of the laser scanning data (Hansen et al., 1999).

1.2.3 Least squares interpolation

This method is based on the well-known approach to create a DTM from a covariance function that is empirically derived from the height data (Kraus, 2000). After a preliminary adjustment using equally weighted laser points, new weights are computed by a special asymmetric weighting function and the initial residuals. Gross errors and points with a significant distance to the reference surface are iteratively weighted down and finally discarded in the subsequent adjustment if a certain threshold is reached. At the end of the process, the laser point cloud is cleaned from vegetation points. The method is robust with respect to gross errors and vegetation points and describes statistically the measured laser scanning data. A data pyramid is used in which the point density and the morphology of the data changes in dependence on the pyramid level (Briese, 2002; Pfeiffer, 2001).

1.2.4 Slope based filtering

Vosselman et al. (2001) describe an approach that uses the slope as a filter criterion. Laser points are just accepted as terrain points if the height to the neighbouring points does not change significantly. The filtering process depends on the point density and the height differences of the terrain. Axelson (2000) starts from a coarse TIN DTM and refines the DTM using distance and angle criteria so that vegetation points and house edges can be detected. Because of the geometrical constraints this method takes also into account the local height differences in the data.

2. ROBUST FILTERING WITH FINITE ELEMENTS

2.1 Key idea

The key idea of this new approach is to combine a robust DTM filtering based on finite elements with a convex hull

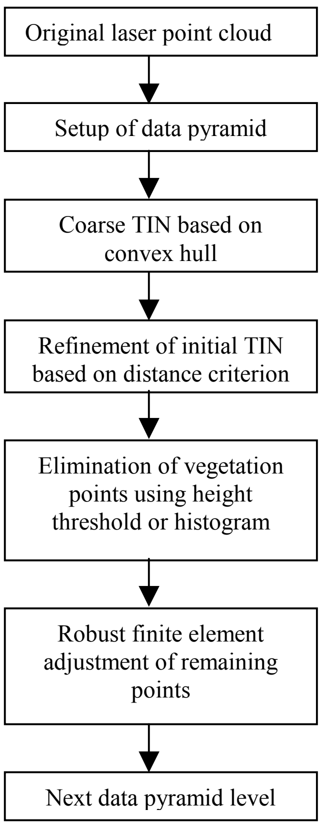

Figure 1. Scheme of laser filtering process

technique. The initial TIN DTM is subsequently refined by laser points that lie at morphological important locations using an appropriate geometrical distance threshold. Non-terrain points like vegetation points and extremely outlying laser points can be pre-eliminated from the original laser point cloud based on the coarse DTM representation and a height histogram. The TIN DTM is subsequently adjusted in an iterative robust adjustment using the remaining laser points. This leads to a better approximation of the terrain since the height of the TIN points can slightly change according to statistical and geometrical constraints. Observations with large normalized residuals are discarded by special weighting functions. The results of the second step are adjusted DTM heights and filtered laser points. Eliminated observations are classified as non-ground points e.g. vegetations points. This filtering scheme is applied in a data pyramid that has three additional layers. The point density in the individual pyramid levels is varied from 4 m to 1 m. Figure 1 shows the general scheme of the approach.

2.2 Convex hull

This is basically a standard procedure, which is not described in much detail. So far, we use public domain code that automatically creates a convex hull from a 3D point cloud (Geometry Center, 2002). The result of the algorithm is a TIN representing the lowest laser points. The refinement of the crude TIN DTM at morphological important features is achieved by embedding some additional laser points that have a certain distance to the initial DTM. For that purpose we use a simple divide-and-conquer algorithm along the scan lines.

2.3 Mathematical approach of DTM filtering

The TIN DTM is subsequently adjusted using robust finite elements.

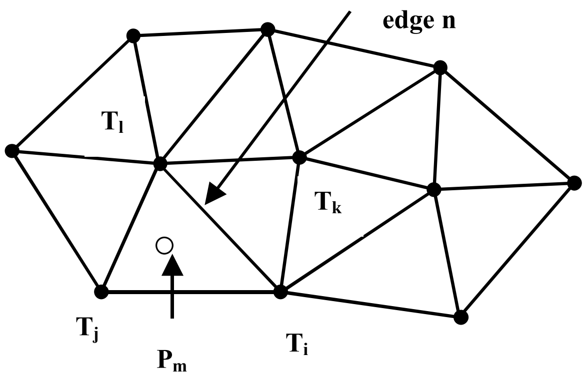

Figure 2. TIN DTM

In the TIN DTM defined by the s TIN points

$T_r\ (X_r, Y_r, Z_r)\ (r = 1,s)$

t laser points $P_m\ (X_m, Y_m, H_m)$ $(m = 1,t)$ are measured with the height standard deviation σ_{H_m}.

For a given pair of triangles and a measured laser point P_m (X_m, Y_m, Z_m) the following linear observation equations are introduced

$$H_m + v_m = f(Z_i, Z_j, Z_l) = A_1 \cdot Z_i + A_2 \cdot Z_l + A_3 \cdot Z_j \quad (1)$$

$$H_r + v_r = Z_r \quad (r = i, j, k, l) \quad (2)$$

$$V_u + v_{V_u} = g(Z_i, Z_j, Z_l, Z_k) = B_1 \cdot Z_i + B_2 \cdot Z_k + B_3 \cdot Z_j + B_4 \cdot Z_l \quad (3)$$

with

$$A_1 = \frac{(X_l \cdot Y_j - X_j \cdot Y_l) - (Y_j - Y_l) \cdot X_m + (X_j - X_l) \cdot Y_m}{D}$$

$$A_2 = \frac{(X_j \cdot Y_l - X_i \cdot Y_j) - (Y_i - Y_j) \cdot X_m + (X_j - X_i) \cdot Y_m}{D}$$

$$A_3 = \frac{(X_i \cdot Y_l - X_l \cdot Y_i) - (Y_l - Y_i) \cdot X_m + (X_l - X_i) \cdot Y_m}{D}$$

$$D = (X_l \cdot Y_j - X_j \cdot Y_l) - (Y_j - Y_l) \cdot X_i + (X_j - X_l) \cdot Y_i$$

$$B_2 = \left(\frac{dX_3 \cdot dY_4 - dY_3 \cdot dX_4}{l_3 \cdot l_l} \right)$$

$$B_3 = \left(\frac{dX_4 \cdot dY_2 - dY_4 \cdot dX_2}{l_2 \cdot l_l} \right)$$

$$B_4 = \left(\frac{dX_2 \cdot dY_3 - dY_2 \cdot dX_3}{l_2 \cdot l_3} \right)$$

$$B_1 = -B_2 - B_3 - B_4$$

$$dX_r = X_r - X_i$$
$$dY_r = Y_r - Y_i$$
$$l_r = \sqrt{(dX_r)^2 + (dY_r)^2}$$
$$r = j, k, l.$$

Equation (1) represents the height interpolation for the point P_m in the triangle given by the TIN heights Z_i, Z_j, and Z_l. Equation (2) is the simple observation equation for the unknown TIN heights Z_r (r=i, j, k, l) for which laser points with heights H_r are measured. Finally, equation (3) represents the complanarity constraint between the three vectors $\overrightarrow{T_iT_k}$, $\overrightarrow{T_iT_l}$ and $\overrightarrow{T_iT_j}$ that are defining the parallelepiped with the TIN points T_i, T_j, T_k, and T_l. The value computed in (3) is also equivalent to the volume in the parallelepiped normalized with the planimetric distances l_r. Z_i, Z_j, Z_k and Z_l are the unknown heigths in the two triangles.

The stochastic model completes the mathematical model with the expectation values for the observations

$$E(H_m) = 0 \qquad (m = 1,t)$$
$$E(V_u) = 0 \qquad (u = 1,n) \text{ (n:number of edges)}$$

and their a-priori weights

$$p_{H_m} = \frac{1}{\sigma^2_{H_m}} \quad (m=1,t)$$

$$p_{V_u} = \frac{1}{\sigma^2_{V_u}} \quad (u=1,n)$$

derived by the standard deviations σ_{H_m} and σ_{V_u} .

The introduction of special weighting functions, which influence the initial weights by the normalized residuals n_v of each observation, leads to a robust adjustment scheme. The weighting functions are

$$w_1(n_v) = \frac{1}{\sqrt{1 + (n_v)^2}}$$

and

$$w_2(n_v) = e^{-(n_v)^2} .$$

The weights are modified in each iteration step by

$$p_H^{(\nu+1)} = p_H^{(0)} \cdot w_q(n_{v_H}^{(\nu)})$$

$$p_V^{(\nu+1)} = p_V^{(0)} \cdot w_q(n_{v_V}^{(\nu)})$$

(q=1,2) (ν: Iteration step)

in a 2-step Gauß-Markoff process. Observations with large normalized residuals are weighted down and are even eliminated if a certain threshold is reached (Krzystek at al., 1992). The solution for the DTM heights is found in an iterative adjustment step by minimising the function

$$f(Z_r, \sigma_H, \sigma_V) = v_H^T p_H^{(\nu)} v_H + v_V^T p_V^{(\nu)} v_V$$

until the estimated values for σ_H und σ_V become constant or reach a threshold.

2.4 Discussion

The method estimates the accuracy of the adjusted terrain heights based on the normal equation matrix and the sigma naught. Thus, a self-diagnosis is possible after the classification of the terrain points. Equation (3) plays the role of a geometrical constraint between the two neighbouring triangles. Special weights can be used to smooth the DTM or to overcome critical areas where the penetration rate of the laser points was very low. The approach is basically suited to detect break lines that are edges where the additional observations are eliminated by the robust procedure.

The presented approach has been realized in a preliminary system with reduced computational efficiency. For instance, problems exist when the number of triangles per computation unit becomes very large. Furthermore, the generation of the data pyramid is not optimised and the patch wise management of the triangles is not solved.

3. RESULTS

So far, we have solely tested the method in wooden areas, which have been flown by the TopoSys system (Loebe, 2001; Fischer et al., 2003).

3.1 Test area

The test site is located in the National Park Bavarian Forest that has been selected for the HTO research project “Development of new methods in mensuration of forest structures” (Kennel, 2001). The general goals of the research project are to investigate the suitability of techniques like laser scanning, InSAR and photogrammetry for the derivation of forest characteristics. Special forest parameters, which are so far to be captured in time consuming campaigns with considerable manpower, should be derived automatically from the sensor data of the mentioned measurement techniques. The National Park Bavarian Forest is characterized by large closed forest areas and provides different forest structures that are very well suited for this particular research project.

Four major test areas B – E have been established in which 22 special reference areas have been defined with a area size of 1800 m^2 to 6000 m^2. They represent different forest structures in order to test laser scanning under changing conditions. In general, the topography of the sub areas can be characterized as undulating terrain with the exception of the flat sub areas B1 – B4, C1 and C5. The sub areas B1 – B4 represent difficult terrain for the DTM filtering because of the large amount of deadwood. For each sub area numerous ground truths were measured by tacheometry and DGPS. Their absolute accuracy was comprehensively checked and can be estimated to 1 – 2 cm. The check points had been especially placed beneath and beside of trees, at stumps, on lying deadwood and at morphological important features. Figure 3 shows the location of the four test areas in the National Park Bavarian Forest.

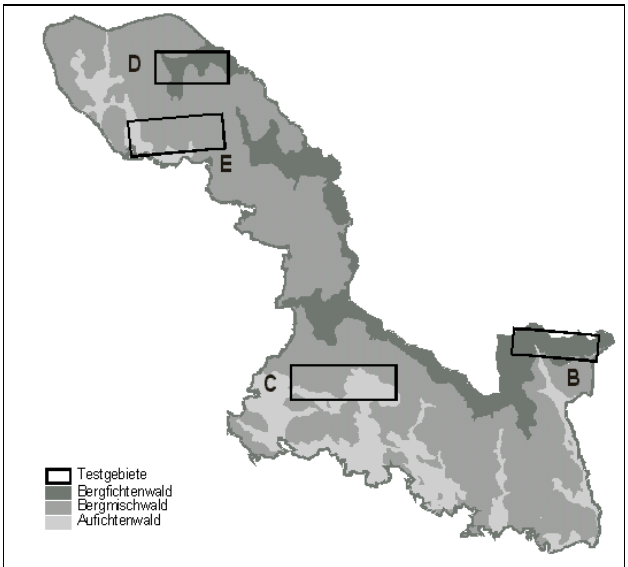

Figure 3. Test areas

The four test areas were flown by the TopoSys II scanner in spring-time (April/May) and summer-time (September) in first-and-last pulse mode. Area C was just flown in last pulse mode. The TopoSys II scanner provides at the flown flying height of 850 m a point density of approximately 5 points/m^2. The accuracy assessment of the laser strips with special check points measured with DGPS showed an absolute accuracy of 10 – 15 cm in full accordance with the technical specifications of the TopoSys system (Fischer et al., 2003).

3.2 Accuracy assessment

DTMs were filtered with the preliminary system for each sub area using the laser measurements of the spring-time campaign. The accuracy assessment of the filtered DTMs was carried out with the numerous check points being available in the sub areas. Standard deviations were evaluated as r.m.s. values from height differences that were derived by bilinear interpolation of the check points into the DTMs. The r.m.s. values were bias corrected assuming that the laser measurements had a constant height shift due to systematic effects of the laser scanning system. For comparison reasons the same procedure was applied to the DTMs filtered by TopoSys. Table 1 shows the result of this accuracy check and some other statistical parameters of the sub areas. Figure 4 shows graphically the empirical standard deviations for all sub areas.

Sub area	Type	point density $[\frac{pts}{m^2}]$	# check pts	Penet. rate [%]	r.m.s. Finite Elem. [m]	r.m.s. Topo. DTM [m]
B1	Deadwood	4	498	38	0.202	0.191
B2	Deadwood	4	813	74	0.201	0.192
B3	Deadwood	4	649	72	0.210	0.201
B4	Deadwood	5	714	55	0.223	0.221
C1	Coniferous	5	563	38	0.172	0.179
C2	Deciduous	12	151	92	0.182	0.185
C3	Con./Dec.	9	169	85	0.162	0.163
C4	Con./Dec.	10	678	83	0.231	0.231
C5	Deciduous	13	401	92	0.284	0.271
C6	Con./Dec.	8	321	97	0.117	0.118
D1	Coniferous	4	568	34	0.158	0.155
D2	Coniferous	5	466	20	0.162	0.161
D3	Coniferous	5	337	3	0.251	0.251
D4	Coniferous	4	262	22	0.213	0.224
E1	Coniferous	4	204	21	0.342	0.380
E2	Coniferous	6	172	30	0.256	0.255
E3	Coniferous	4	248	46	0.276	0.298
E4	Coniferous	6	176	27	0.303	0.338

Table 1. Statistics of sub areas

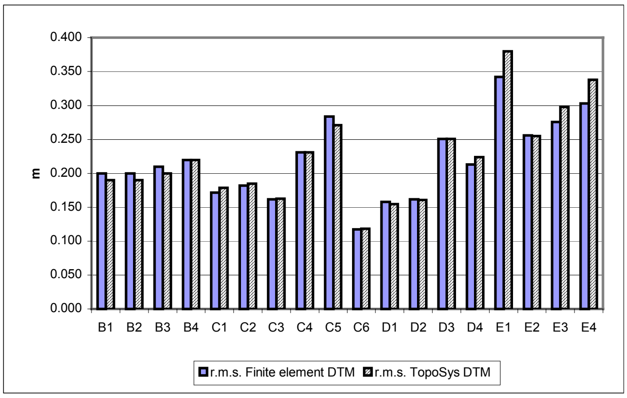

Figure 4. DTM Standard deviation of sub areas

From those results the following conclusions can be drawn.

- The DTMs filtered by the presented finite element approach show an accuracy in the range of 0.15 m – 0.25 m.
- Larger values (E1, E3, E4) are mainly caused by the low penetration rate in almost closed coniferous sub areas. Morphological features and other DTM details could not fully be detected because of missing terrain points.
- The mean standard deviation of 0.20 m in the flat areas B1 – B4, which have a considerable high penetration rate, is probably influenced by deadwood that could not be completely filtered by the algorithms.
- The standard deviations of the presented approach correspond very well with the standard deviations derived from the TopoSys DTM.

Figure 5 and 6 shows exemplary two profiles of the sections C3 and E4 indicating a considerable good correspondence between the two filtered DTMs.

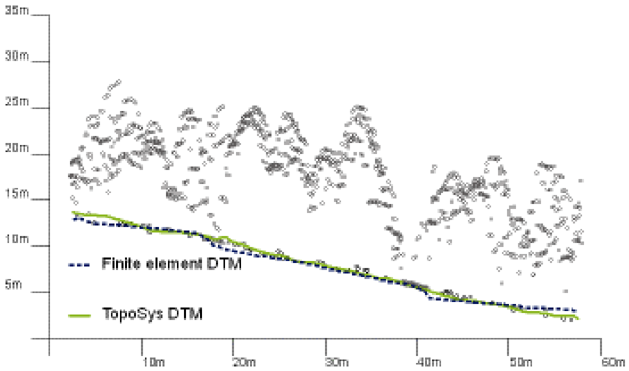

Figure 5. Filtered DTM in profile (sub area C3)

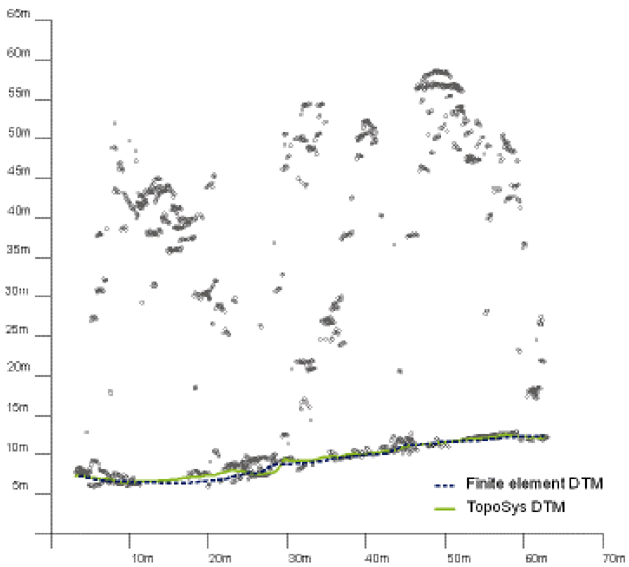

Figure 6. Filtered DTM in profile (sub area E4)

4. CONCLUSIONS

The paper gives an introduction to a new filter approach for laser scanning data based on robust finite elements. The finite elements are triangles that are derived from the original laser points. The first preliminary results indicate that DTMs can be determined accurately enough in forest areas. The accuracy derived in controlled tests is equivalent to standard procedures for filtering of laser scanning data.

Future work will be focussed on the application of the system to laser scanning data that are not captured in forest areas. Furthermore, investigations will be carried out in how far the approach can detect break lines.

As far as the system is concerned it is planned to improve the overall system performance and to enable a patch wise processing of laser scanning data.

5. ACKNOWLEDEGMENTS

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