DEM GENERATION FROM LASER SCANNER DATA USING ADAPTIVE TIN MODELS

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ABSTRACT

Generation of DEMs from laser scanner data requires processing of the original data points. Data must be filtered in order to eliminate measurements not belonging to the ground surface. A filtering algorithm based on Triangular Irregular Networks, TIN, is developed. A sparse TIN is created from seed points and densified in an iterative process. The TIN adapts to the data points from below and is constrained in its curvature by data derived parameters. The algorithm handles surfaces with discontinuities and is developed with dense city areas in mind where such discontinuities may appear. A version of the algorithm is implemented in a commercial software package from TerraSolid. It is tested on both synthetic and real data from the TopEye system. An independent accuracy evaluation of the result is presented.

1 BACKGROUND

One of the main tasks solved by laser scanning has been the one of high quality DEM. Especially in forestry areas with dense vegetation has the ability of penetrating the canopy been an important feature compared to traditional image based photogrammetry and good results have been reported, *e.g.,* Kraus and Pfeifer (1998). The filtering process is often treated as a local operation on data which is suited for areas with continues surfaces but may cause problems in areas with complex, discontinued ground surfaces like dense city areas or complex construction sites. The work in this article is concentrated on data sets from such areas, where a high point density, > 1pnt/m^2, is needed. The final delivered DEM if often not as dense, especially if delivered as a TIN, but the high point density is needed in order to find structures and breaklines in data. The examples shown in the article has an accuracy of less than 0.1 m on hard surfaces. This accuracy enables the use of laser data in many engineering tasks, but do also mean that filtering of data must be carried out in a correct manner. Rounding errors on sharp edges or ridges can have a significant effect in such cases. The high accuracy of data is only possible to reach if a thorough system calibration has been carried out. In many cases it is also needed to do an adjustment of several strips in order to eliminate drift parameters in the INS system, Burman (2000), Haala et al. (1997). High accuracy DEM from laser scanner data is a product that will probably be used more frequently in the future as system and software are improving.

2 LASER SCANNERS AND LASER SCANNER DATA

A laser scanning system produces data, which can be characterised as sub-randomly, distributed 3D point clouds. These point clouds may contain more information than a 2.5D surface model, in which the elevation has a unique z-value as a function of x and y. This means that vertical walls in certain cases can be seen as truly vertical, surface points beneath bridges can be measured and volumetric estimations of vegetation can be carried out. Elevation data can be acquired with different attributes depending of application and laser scanner system. Some of these attributes effecting filtering and modelling algorithms are:

- Point density
- Registrations of multiple echoes
- Amplitude registration (reflectance)

The point density is depending on flying height but also on system dependent factors, such as platform velocity, field of view, and sampling frequency. The point density should be adjusted according to the application. For modelling applications, like 3D City models or power line surveys, the requirements of the point density are very different from the task of generating DEMs with grid sizes of 5-10 m.

The second attribute, multiple echoes of one laser pulse, can also be registered by some systems. This can be of importance in filtering and modelling algorithms related to vegetation and ground surface separation and volume estimations in forestry applications. Multiple echoes can also be found at the edges of buildings, thus indicating a very fast change in elevation.

The last attribute, amplitude or reflectance registration gives radiometric information about the surveyed area. The reflectance can be seen as an “image” in a very narrow wavelength band. It can be used in classification algorithms, *e.g.,* separating paved areas from grassland.

2.1 Data used in the examples

Data used in the examples presented in this article are acquired from the TopEye system. The primary sensor of the TopEye system is the laser range finder, LRF. The LRF sensor measures distances between the aircraft and the ground at a frequency of 7 kHz with up to four distances recorded by each laser pulse. It has a sampling density of 0.25 - 5 m at flying heights of 50-1000 m and a footprint of 0.1-2.5 m. The pulsed laser beam is scanned across the track of the helicopter or airplane, creating a Z-shaped pattern. The position and attitude of the helicopter are determined by differential GPS and INS. Ground points are measured with a nominal accuracy of 0.1-0.3 m depending on altitude, Figure 1. The TopEye system has the possibility to register the amplitude of the returning laser pulse. Even if the noise level of the reflectance data is higher than for a film- or high resolution CCD-image it can still be used in some applications.

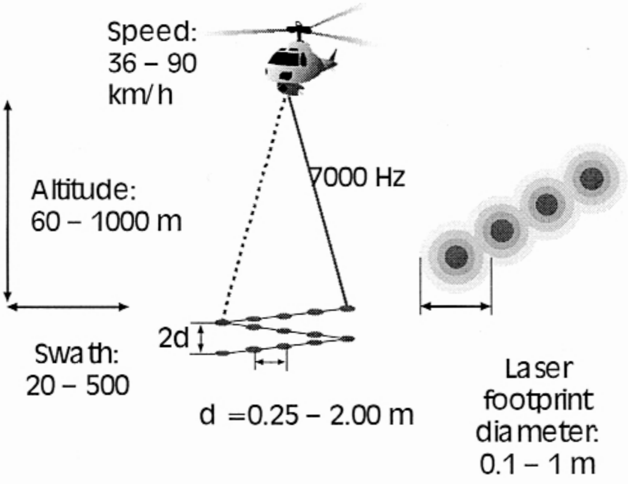


Figure 1 Principles of the TopEye system

3 FILTERING APPROACH - ADAPTIVE TIN-SURFACES

The processing of laser scanner data often aims at either removing unwanted measurements, either in the form of erroneous measurements or objects, or modelling data given a specific model. Removing unwanted measurements, as in the case of finding a ground surface from a mixture of ground and vegetation measurements, is here referred to as filtering. Some information in the original sub-randomly distributed 3D point clouds is lost if data are interpolated into a regular grid, *i.e.,* a DSM. The loss of information can be significant, especially if multiple echoes are registered in forested areas, since points with similar xy-coordinates but at different elevation are difficult to represent in such form. For this reason, we believe that original data should be used when processing laser data until an object dependent representation and generalisation can be made.

3.1 Outline of the algorithm

A surface, represented by a TIN, is connected from below to the sub-randomly distributed laser points. The surface adapts to the points and new points are added only if they meet certain data derived threshold parameters, Figure 2.

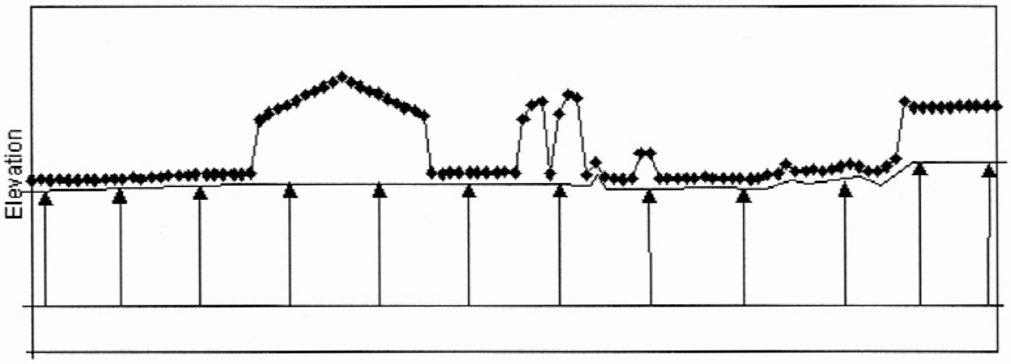


Figure 2 Connecting TIN surface to laser data

The threshold parameters are estimated from data and changes during the filtering process. The algorithm is an iterative process where a coarse TIN consisting of initial seed points is densified. In short, the process can be described as:

- Calculate initial parameters using all data
- Select seed points
- Iterative densification of the TIN
  - Calculate parameters for each iteration from points included in the TIN
  - Add points to the TIN if below threshold values
- Continue until all points are classified as ground or object

3.2 Parameter estimation

Parameters for the TIN densification, distance to the TIN facets and angels to the nodes, are derived from data. A forest area will have a different characteristics compared to an urban area. In the former case small variations in the ground are likely to be accepted, while in the second case a rather flat surface with occasional discontinuities can be expected. Statistics from data is collected in the form of discrete histograms of surface normal angles and elevation differences to enable fast calculations of median values, Figure 7,11,15,19. Parameter thresholds based on median values are estimated from the histograms and used in the iterative process.

In the initialisation phase, before the TIN is created, statistics are collected from the all laser data along the scan lines. After initialisation, statistics is collected only from points included in the TIN.

3.3 Selecting seed points

Seed points are selected within a user-defined grid, which grid size is based on the largest type of structure, e.g., building, that is present in the area. The algorithm is not sensitive to the selection of seed points and a value between 50 and 100 m has proved to be a good selection.

3.4 Densification of the TIN

For each iteration, one point at a time in each TIN facet is added if it meets the criteria based on the calculated threshold parameters. Distances to the facet planes and angels to the nodes are the main values compared, *Figure 3*. Threshold parameters for these values are computed from data at each iteration. This algorithm for densification is valid for continues surfaces, such as normal landscapes. Discontinuous surfaces, which are rather frequent in urban areas, are more difficult to handle. Edges are easily cut off since the threshold values are exceeded, Figure 4

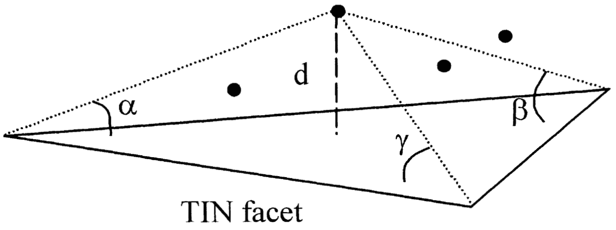


Figure 3 Calculated values for a data point during TIN densification

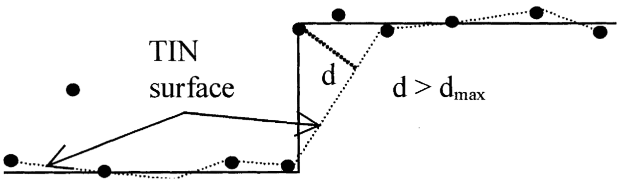


Figure 4 Cutting off edges

Looking not only at the TIN facet circumventing the point, but also in the surrounding area solves the cutting-off problem. The point is mirrored to the closest node point and the deviation from that TIN facet is calculated, Figure 5 and Figure 6. For each iteration, the TIN will now expand in the direction of the discontinuity.

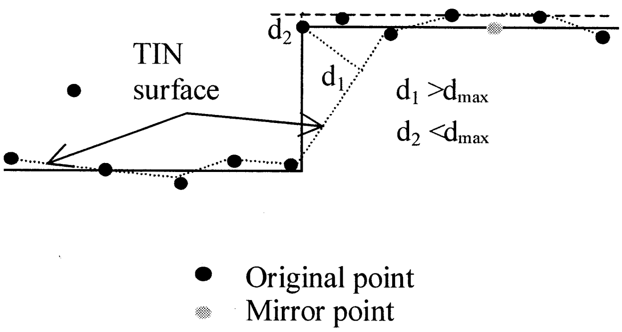


Figure 5 Managing edges in discontinuous surfaces

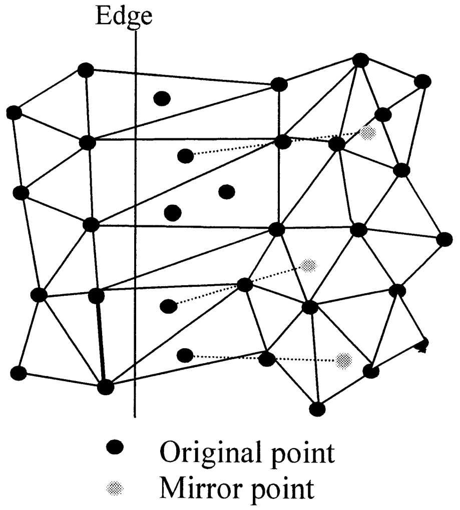


Figure 6 Managing edges in discontinuous surfaces

The iterative process is stopped when no more points are added to the TIN surface. In the implemented software it is also possible to stop the procedure when reaching a given length of the TIN vertices. This is useful for large data sets where computation time and memory allocations can be of importance.

4 EXPERIMENTS

To test and evaluate the method, it was tried on five different data sets. Two of the sets consisted of synthetic data and three sets were from real flights.

4.1 Synthetic data

Two synthetic data sets were constructed to test the method. The data sets are not optimal in any sense, but are used to demonstrate the features and functionality of the algorithm. A gaussian noise, $\sigma=3$, has been added to the data points.

4.1.1 Data set 1 The first data set consists of planar surfaces in terraces with a building at one of the terraces. The algorithm follows the terraces and finds the building at its correct position. The problem of cut-off edges is solved by the iterative procedure where the surrounding TIN facets are examined as well as the TIN circumventing the point.

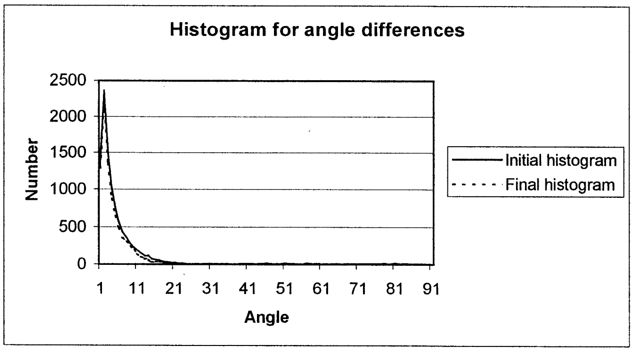
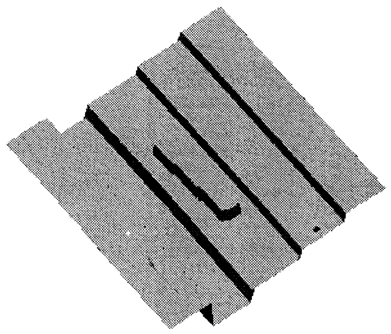
Number of points:	10 000	Classified ground:	8 517
True ground:	9 669	Classified non-ground:	1 483
True non-ground:	331	Non-ground classified as ground:	0
Initial threshold, angle	10°	Ground classified as non-ground:	1 152
Final threshold, angle	3°		
 Figure 7 Accumulated histogram for angle variations		 Figure 8 Original surface	

Figure 9 Profile of surface before and after filtering

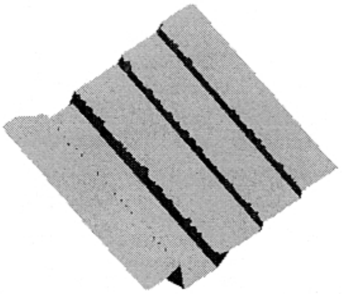


Figure 10 Filtered surface

4.1.2 **Data set 2** The second data set is a dome or hill with some constructions on the hill sides. It is only the large construction that is regarded as a building. The other constructions are holes or planar surfaces connected to the ground surface and therefore regarded as ground.

Number of points:	9891	Classified ground:	9165
True ground:	9 609	True non-ground:	282
True non-ground:	282	Non-ground classified as ground:	0
Initial threshold, angle	47°	Ground classified as non-ground:	444
Final threshold, angle	3°		

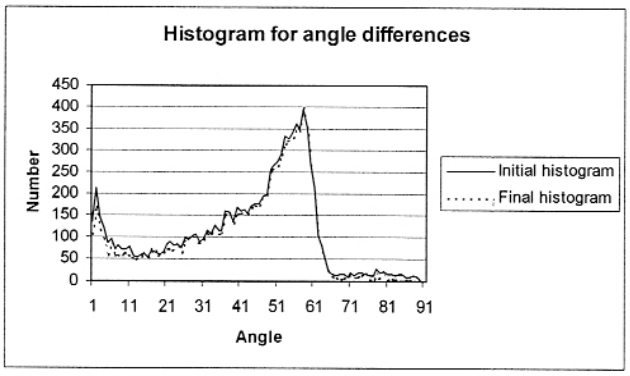


Figure 11 Accumulated histogram for angle variations

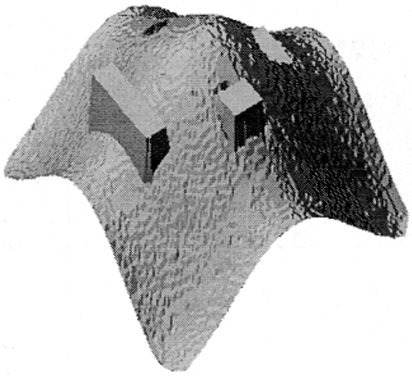


Figure 12 Original surface

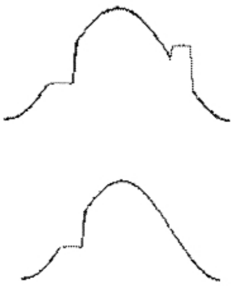


Figure 13 Profile of surface before and after filtering

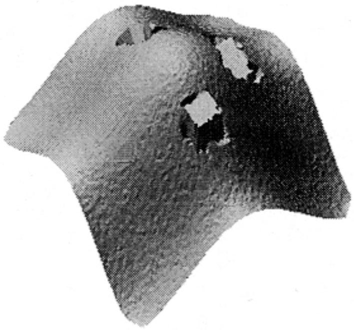


Figure 14 Filtered surface

4.2 Real data

The three data sets are acquired with the TopEye laser system on a helicopter platform with a typical flying height of 350 m. This enables a high point density and high point accuracy.

4.2.1 Data set Stockholm The data set covers an area of central Stockholm. The large building is part of the Royal Castle. The ground surface consists of several terraces which can be hard to distinguish from the buildings.

Number of points: 195 993
Initial threshold, angle 4°
Final threshold, angle 3°

Classified ground: 143 556
Classified non-ground: 52 437

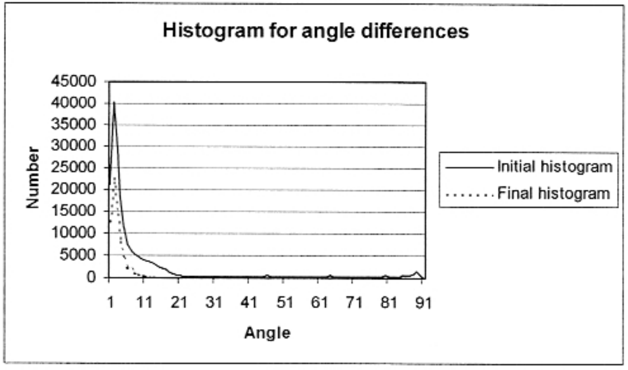


Figure 15 Accumulated histogram for angle variations

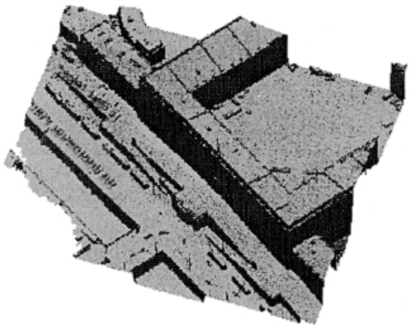


Figure 16 Original surface

Figure 17 Profile of surface before and after filtering

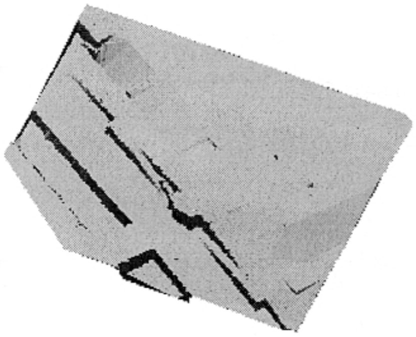


Figure 18 Filtered surface

4.2.2 Data set Arlanda Data covers part of a construction site at Arlanda airport. The DEM was used for volume estimations.

Number of points: 273 719
Initial threshold, angle 6°
Final threshold, angle 2°

Classified ground: 210 829
Classified non-ground: 62 890

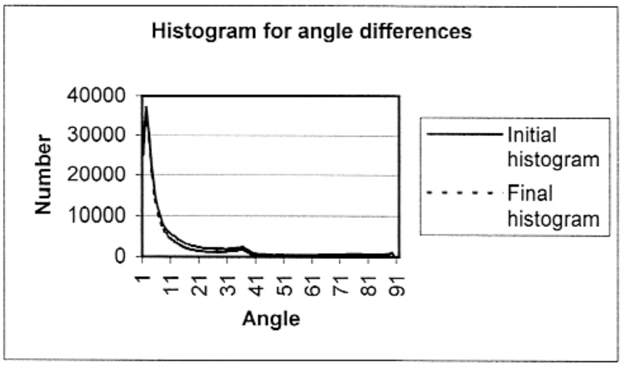


Figure 19 Accumulated histogram for angle variations

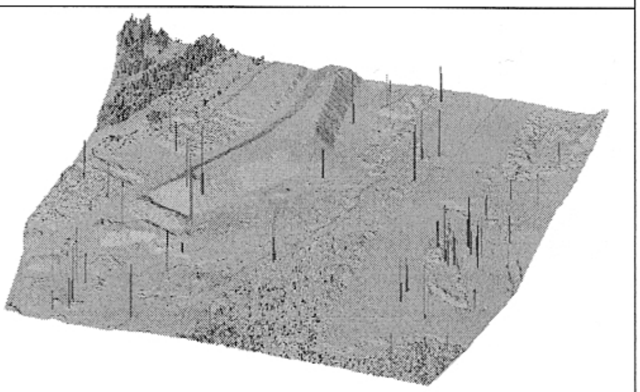


Figure 20 Original surface

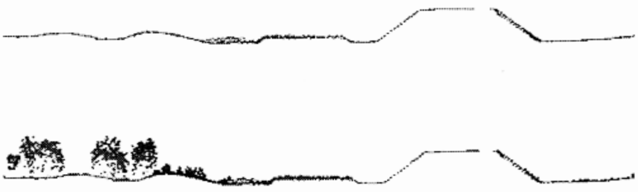


Figure 21 Profile of surface before and after filtering

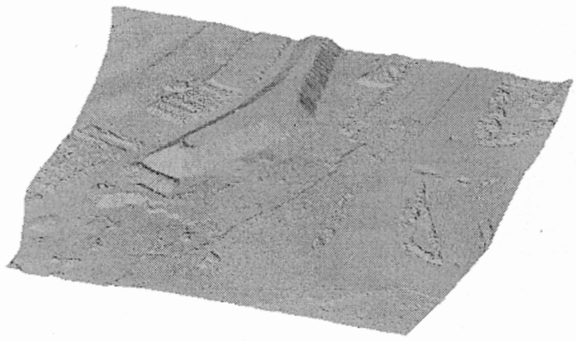
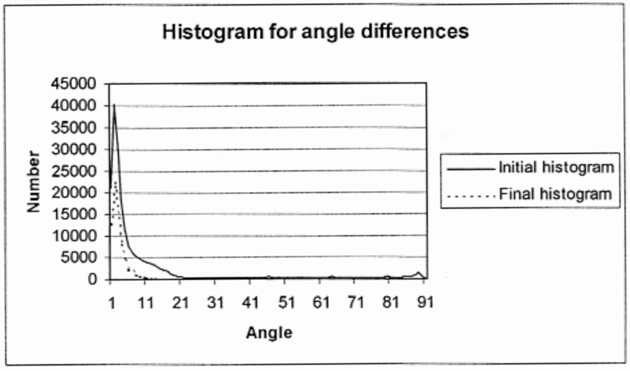


Figure 22 Filtered surface

4.2.3 Data set Kymlinge Data was acquired for road design and construction outside Stockholm. Accuracy requirements were <0.1 m in interpolated ground points. The area consists of a mixture of forests, buildings and existing roads.

Number of points:	216 571	Classified ground:	210 829
Initial threshold, angle	40°	Classified non-ground:	62 890
Final threshold, angle	6°		



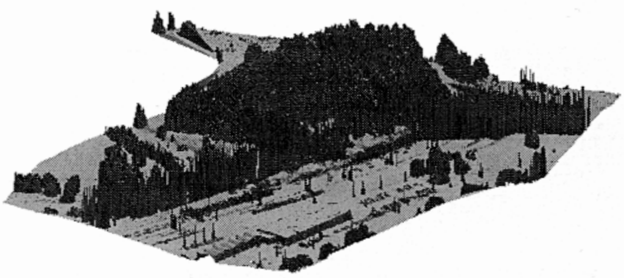


Figure 23 Original surface

Figure 24 Profile of surface before and after filtering

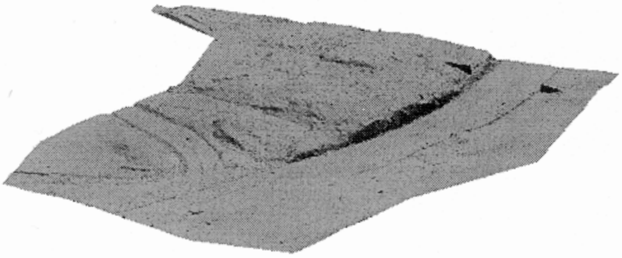


Figure 25 Filtered surface

5 RESULTS

The tests show that the algorithm works satisfactory or good in most types of landscape and city areas. The tests are performed on very high density data, > 1pnt/m^2, which is typical for laser scanners using helicopter platform. There is however no reason to believe that it will behave differently on less dense data, but it has not been proven in any tests.

5.1 Synthetic data

The synthetic data sets illustrate the performance in terraced landscapes and structures on steep hillsides. The number of non-ground points classified as ground is in both case zero, while there are ground points classified as non-ground. In data set 1 these are points that have a high random noise value added. In data set 2 the erroneously classified points are located around the deviations from the dome, i.e., the whole and the flat surfaces. Further refinement of the densification process of the TIN is needed to solve these problems.

5.2 Real data

The two last data sets, Arlanda and Kymlinge, have been independent evaluated by the end-user. Different types of control measurements were made in the areas. Table 1 and Table 2 shows the result from the evaluation. For hard surfaces, like roads and paved areas, the mean difference is below 0.05 m. in dense bush vegetation, laser measurements will have a higher value than the true surface. Since the measurement is integrated over an area, the problem is hard to overcome.

Data set	**Type**	**Control measurement**	**No points**	**Mean difference**	**Std of differences**
1	Planar surface	Interpolated DEM	4	0.02 m	0.06 m
1	Mixed terrain	Interpolated DEM	48	0.14 m	0.03 m
2	Dense bushes	Exact laser point	13	0.19 m	0.08 m

Table 1 Evaluation of Arlanda and Kymlinge data set

Data set	**Type**	**Control measurement**	**Size of DEM (m^2)**	**Volume difference**	**Equivalent height difference**
2	Road surface	Comparing DEM	7180	336 m^3	0.09 m
2	Dense forest	Comparing DEM	3895	189 m^3	0.026 m

Table 2 Evaluation of Arlanda and Kymlinge data set

6 DISCUSSION

Airborne laser scanner systems have become accepted as an alternative tool to photogrammetry within certain applications. The generation of DEMs is such an area where laser scanning shows some advantages. This paper has concentrated on DEMs of very high density and accuracy and shown that DEMs with mean error of less than 0.05 m on well defined surfaces are possible to reach. This opens new areas of applications in engineering measurements like road construction and design.

Calibration and good campaign procedures are key issue if such results are to be expected at a regular basis. More standardised and open methods for adjustment procedures will also increase the acceptance of laser scanning in new applications.

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