

Processing of laser scanner data—algorithms and applications

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Received 5 October 1998; accepted 2 December 1998

Abstract

Airborne laser scanning systems are opening new possibilities for surveys and documentation of difficult areas and objects, such as dense city areas, forest areas and electrical power lines. Laser scanner systems available on the market are presently in a fairly mature state of art while the processing of airborne laser scanner data still is in an early phase of development. To come from irregular 3D point clouds to useful representations and formats for an end-user requires continued research and development of methods and algorithms for interpretation and modelling. This paper presents some methods and algorithms concerning filtering for determining the ground surface, DEM, classification of buildings for 3D City Models and the detection of electrical power lines. The classification algorithms are based on the Minimum Description Length criterion. The use of reflectance data and multiple echoes from the laser scanner is examined and found to be useful in many applications. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: laser scanner; 3D City Models; classification; modelling; filtering; MDL

1. Background

Laser scanner systems available on the market are presently in a fairly mature state of art, where most of technical hardware difficulties and system integration problems have been solved. The systems are very complex, being more a ‘geodetic’ system on the data acquisition part and more a ‘photogrammetric’ system on the data processing part.

What very much remains is the development of algorithms and methods for interpretation and modelling of laser scanner data, resulting in useful representations and formats for an end-user. The basic

processing task of separating the bare ground surface from objects on the surface, i.e., defining a digital elevation model, DEM, as a subset of a measured digital surface model, DSM, needs to be investigated more profoundly. Also, more application dependent tasks, such as classification of objects, 3D City modelling and engineering surveys need to be studied. Existing software are, in general, propriety software or university products. Commercial software not connected to a specific laser scanner system are offered by a very limited number of companies.

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 infor-

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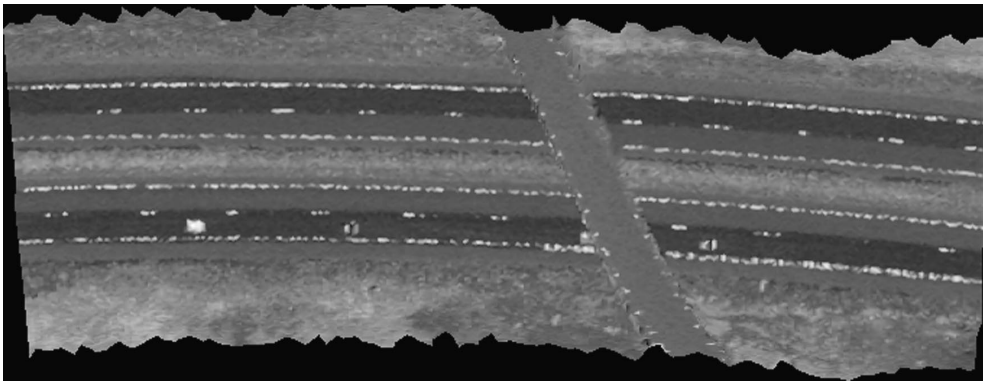


Fig. 1. Reflectance image of road survey.

mation 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 on application and laser scanner system. Some of these attributes affecting filtering and modelling algorithms are:

- point density
- registrations of multiple echoes
- amplitude registration (reflectance).

The point density is dependent on flying height and also on system dependent factors, such as plat-

form 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.

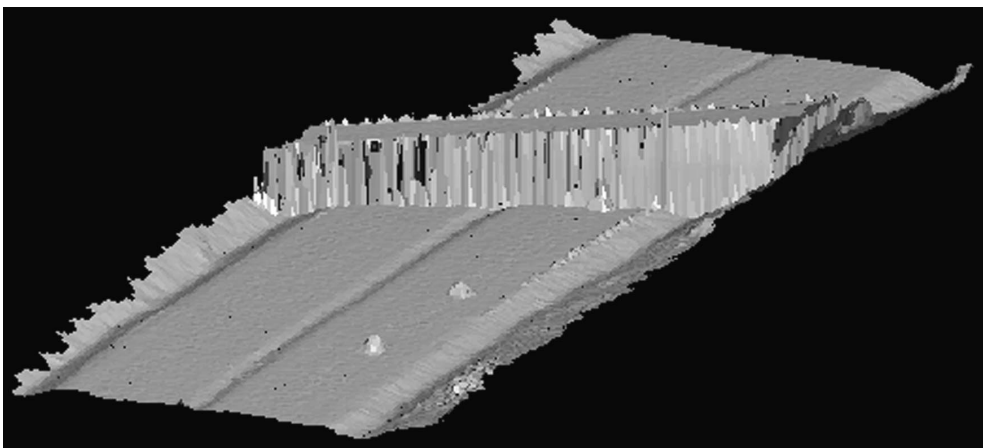


Fig. 2. Perspective view of elevations.

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 wave length band. It can be used in classification algorithms, e.g., separating paved areas from grass land (see Figs. 1 and 2).

2.1. Data used in the examples

Data from the Saab TopEye system have been used in the examples presented in this article. 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.

Recent development of the TopEye system makes it possible 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.

3. Processing of laser scanner data

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 in this context referred to as filtering. The unwanted measurements can, depending on application, be characterised as noise, outliers or gross errors. Finding a specific geometric or statistic structure, as buildings or vegetation, is referred to as classification. The generalisation, finally, of the classified objects is referred to as modelling. Filtering, classification and modelling are thus defined according to aim and not to method.

Some information in the original sub-randomly distributed 3D point clouds are 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 (c.f. Fig. 16) since points with similar *xy*-coordinates but at different elevation are difficult to represent in a regular grid. For this reason, we believe that original data should be used in the filtering and modelling process until an object dependent representation and generalisation can be made. For some application, e.g., extraction of power lines, this is almost a necessity since a power line must be described as a true 3D object and not in 2.5D.

Most applications will require special algorithms and strategies for the classification and interpretation of LRF data, but one task can be seen as general to most of these applications and that is the separation of objects from the ground surface. Once the objects

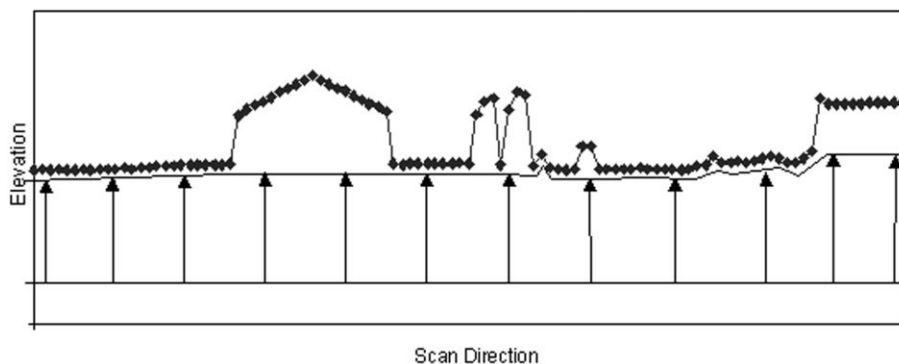


Fig. 3. Connecting ground surface to LRF data.

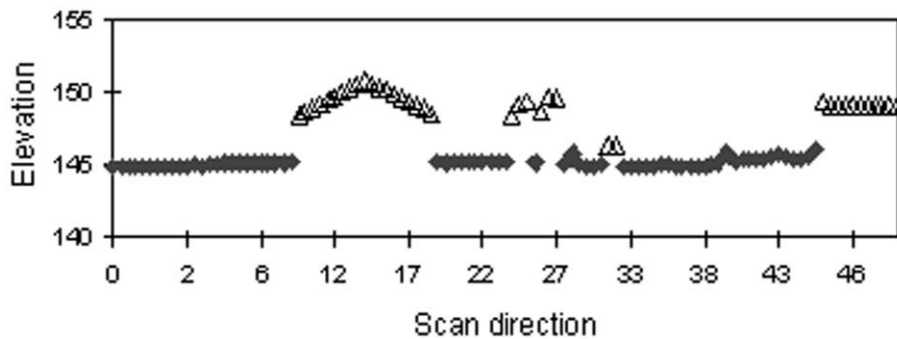


Fig. 4. Separating ground from objects.

are separated from the ground surface, they can be treated by various algorithms according to the application at hand.

Following these ideas, a strategy for the interpretation of LRF data is formulated based on elevation data but with the possibility of adding other types of sensor data if available. The strategy can be summoned as:

- Use original LRF data as long as possible, preferably in a TIN structure for easy access of neighbouring points,
- Separate surface and objects on the surface,
- Develop application dependent algorithms for object classification and modelling.

Other data types, such as reflectance data or information of multiple echoes from the LRF, or existing images and GIS data, should be used and

included in the processing if available (c.f. Haala et al., 1997; Hug, 1997).

3.1. General task—finding the ground surface

Here, a method is developed where a surface is connected from below to the point cloud (see Fig. 3). Only the principles of the method are described here to give a background to the application dependent algorithms. The surface is allowed to fluctuate within certain values. These fluctuations can be controlled by, e.g., Minimum Description Length (MDL) models, constrained spline functions, active contour models like snakes or geometrical thresholds for elevation differences. Some characteristics of the approach is:

- A ground surface of connected points in a TIN is created,

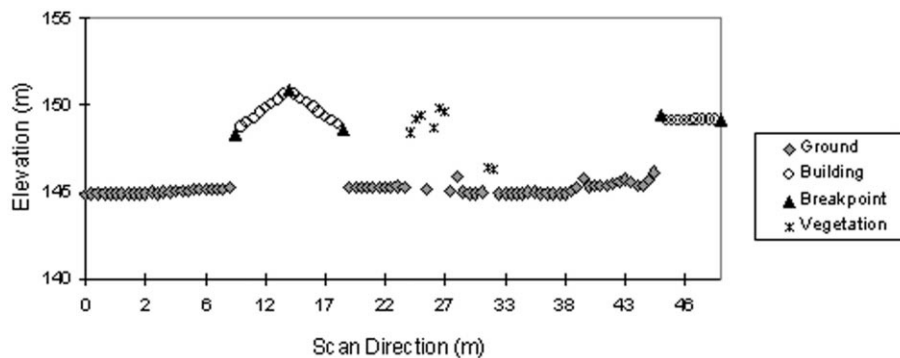


Fig. 5. One classified scan line of suburban area classified in ground, vegetation and buildings with breakpoints.

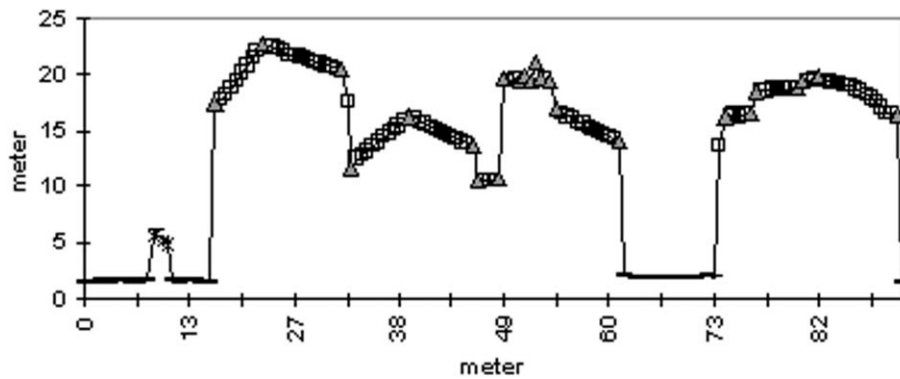


Fig. 6. One classified scan line of urban area.

- It bridges over large surface objects, e.g., industrial plants,
- The surface goes through the original data points,
- Low ground surface points will always be included.

An implementation of a simplified version of the approach was carried out. The implementation analyses each scan line at a time and not at a whole surface. The implementation fails if no ground surface is present in a scan line, but works satisfactory in most cases (see Fig. 4). A surface-based implementation based on TIN will be carried out.

3.2. Classification of buildings

Delineated surface objects consisting of unstructured point clouds linked to a TIN are processed by area-based methods looking at one object at a time. A classification tool is developed that classifies surface objects in the two classes buildings and vegetation. The ability of the laser to penetrate vegetation and thus giving echo from several heights makes it possible to distinguish between the two classes man-made objects and vegetation. The classification procedure is based on an implementation of the MDL criterion for robust estimation (Rissanen, 1983; Axelsson, 1992). A cost function is formulated for the two classes buildings and vegetation based on the second derivatives of the elevation differences. A simplified implementation based on the scan lines was carried out.

The model assumes that buildings consist of connected planar surfaces. Neighbouring TIN facets on the same plane will have the same orientation within a noise level. Similarly, neighbouring scan line points will lie on a straight line with the second derivatives of elevation differences zero. Roof ridges and other changes of direction of the roof will cause a non-zero

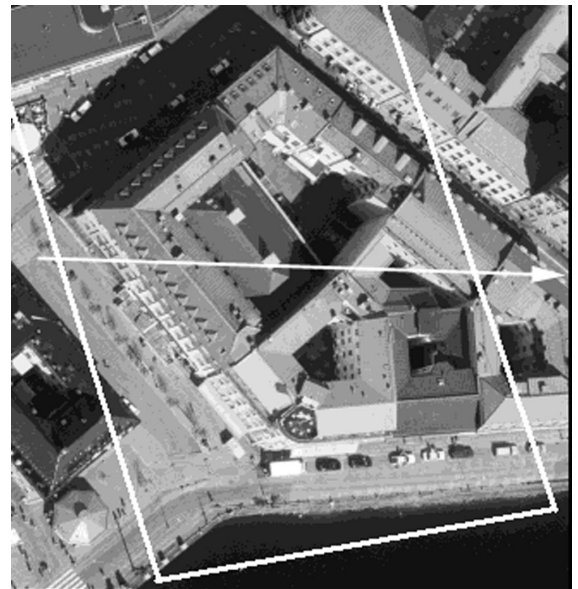


Fig. 7. Scanned aerial photo of the surveyed area. The arrow indicates the scan shown in Fig. 6.

value of the second derivatives. The geometric model of buildings is thus formulated along a scan line as:

$$\frac{\partial^2 z}{\partial x^2} = 0 \quad \text{point} \in \text{Straight line segment} \quad (1)$$

$$\frac{\partial^2 z}{\partial x^2} \neq 0 \quad \text{point} \in \text{Breakpoint}$$

where x is the direction along the scan line and z the elevation.

The cost function, or description length DL, of the building model contains three parts (see Eq. (2)).

- A parametric model for the zero line of the second derivatives. The cost for the model is constant.
- A statistical model for the assumed Gaussian deviations from the parametric model.
- A statistical model for the breakpoints which are assumed to have random behaviour (similar to that of vegetation).

$$\begin{aligned} \text{DL}_{\text{buildings}} = & \text{DL}_{\text{par}} + (\text{DL}_{\text{roof}} + \text{DL}_{\text{gauss}})n_{\text{roof}} \\ & + \text{DL}_{\text{break}}n_{\text{break}} \end{aligned} \quad (2)$$

where

$$\text{DL}_{\text{par}} = C_{\text{constant}};$$

$$\text{DL}_{\text{roof}} = \text{lb}(L/\varepsilon);$$

$$\text{DL}_{\text{gauss}} = \text{lb}((\sigma/\varepsilon) + (1/2))\text{lb}(2\Pi e);$$

$$\text{DL}_{\text{break}} = [(\text{lb}(R_{xy})/\varepsilon) + (\text{lb}(R_z)/\varepsilon)];$$

$$n_{\text{roof}} + n_{\text{break}} = n_{\text{tot}};$$



Fig. 8. LRF data automatically labelled by MDL using the cost function described in Section 3.2 as ground, vegetation and buildings with breakpoints.

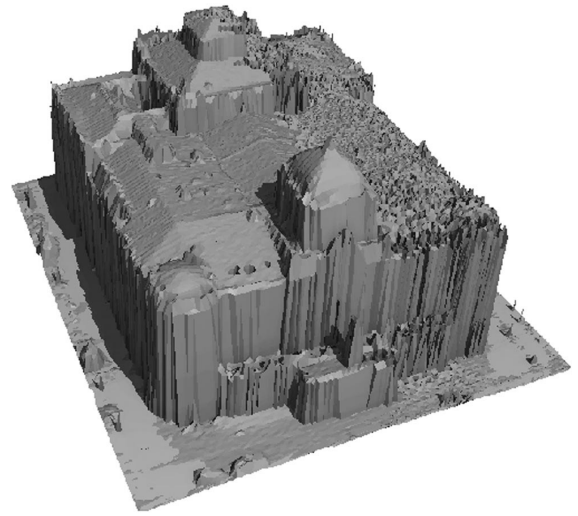


Fig. 9. LRF data displayed as a shaded perspective TIN-model.

- L length or size of building;
- R defines the size of the search space for the building;
- σ^2 the variance of the residuals;
- ε resolution, or accuracy, of data;
- lb binary logarithm with base 2



Fig. 10. LRF data automatically labelled as ground, vegetation and buildings with breakpoints. Only the breakpoints of the building are displayed. Building points between breakpoints have been left out.

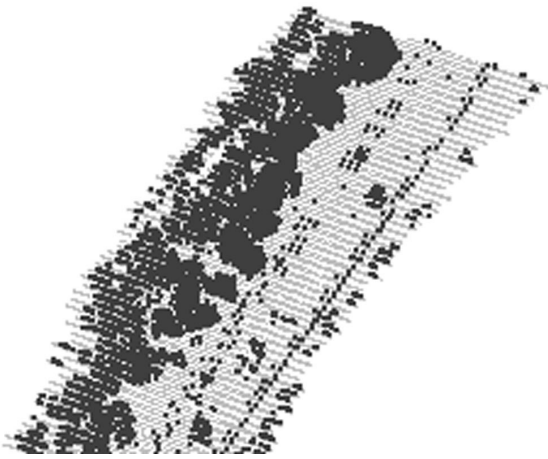


Fig. 11. Step 1: separating ground and objects; 76304 points classified as ground, 23696 points classified as objects.

Vegetation is modelled as points with randomly distributed second derivatives:

$$\frac{\partial^2 z}{\partial x^2} \neq 0 \quad \text{Random behaviour of vegetation points} \quad (3)$$

where x is the direction along the scan line and z the elevation.

The cost function for the vegetation model contains only one part: (i) A statistical model for vegeta-

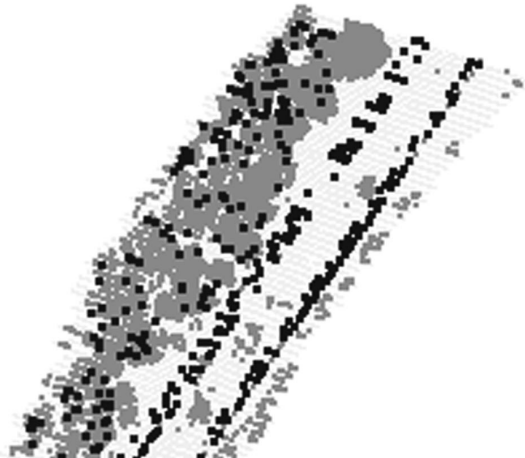


Fig. 12. Step 2: separating vegetation and lines; 22160 points classified as vegetation, 1536 points classified as power lines.

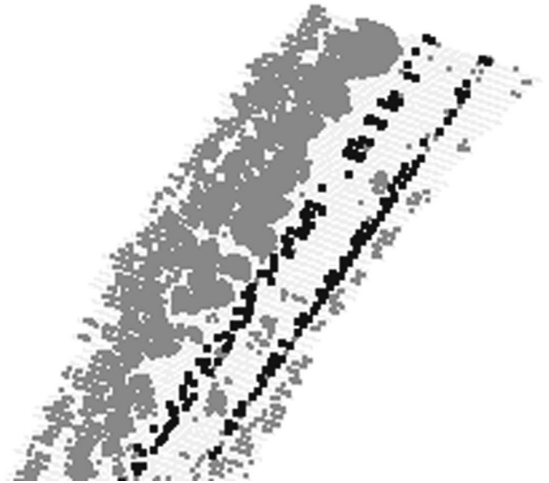


Fig. 13. Step 3: final Hough classification, 76304 points classified as ground, 23024 points classified as vegetation, 672 points classified as power lines, divided on five parallel lines in 2D.

tion which are assumed to have random behaviour (similar to that of breaklines):

$$DL_{\text{veget}} = DL_{\text{rand}} n_{\text{tot}} \quad (4)$$

$$DL_{\text{rand}} = \left[\text{lb} \frac{R_{xy}}{\varepsilon} + \text{lb} \frac{R_z}{\varepsilon} \right].$$

A minimum is located for the building model where the optimum number of breakpoints is balanced against the Gaussian deviation. The minimum cost is compared to the cost of the vegetation model and a classification is made depending of which value is lower. Examples of the classification can be seen in Figs. 5–10. A surface-based implementation based on TIN is under development.



Fig. 14. Accumulated sums of the eight largest cells on the α -axis.

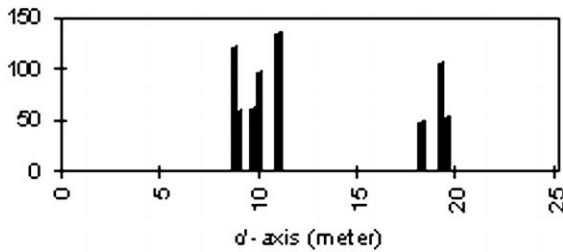


Fig. 15. The eight largest cells of the peak on the α -axis in Fig. 14.

The results from the classification will be input to the next part of the processing, namely object modelling. The modelling should lead to a general description of the building in a CAD/vector representation. A likely solution is a segmentation based on TIN facets and detected breakpoints in combination with a simultaneous least squares adjustment of the segmented planes.

3.3. Classification of electrical power lines

The surveying and modelling of electrical power lines is an application suitable to laser scanning. Using a helicopter as platform makes it possible to follow the line very precisely and to get a dense

point distribution. The classification procedure is divided in the following three steps.

- Separation of ground surface and objects using the model described in Section 3.1.
- Classification of objects in power lines and vegetation using the statistical behaviour of the two classes, including multiple echoes and reflectance values. A power line does almost always give a multiple echo, one from the power line and one from the ground. This in combination with the reflectance value, which is different for power lines and vegetation, gives valuable information.
- Refined classification of power lines by looking for parallel, linear structures in 2D based on Hough transformations.

Since the measured points do not have any direction information, as compared to detected edges in image processing, the search space when using the Hough transformation is rather extensive. Approximate directions to reduce the search can however be obtained from the flying direction if it is a strip along the power line. The line in 2D in the xy -domain is expressed as:

$$x \sin \alpha + y \sin \alpha - d = 0 \quad (5)$$

where α is the direction and d the shortest distance to the line from the origin.

Some observations can be made: (i) d is limited by the region defined by the x - and y -coordinates of

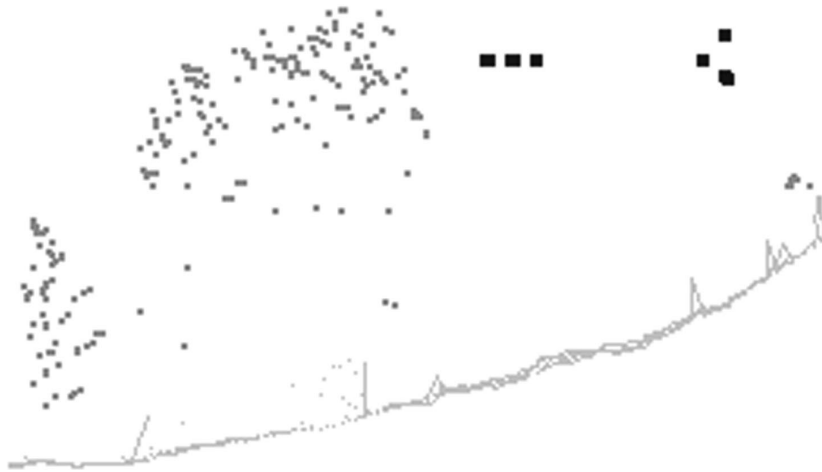


Fig. 16. Cross-section showing ground, vegetation and power lines.

the surveyed area and must be divided into discrete steps coherent with the accuracy of data and object; (ii) All possible directions of lines going through a xy -point will generate a curve in the αd -domain. This extension to the Hough transformation is caused by the lack of direction information for the measured points; (iii) Parallel lines in the xy -domain have the same α but different d values. If they are accumulated on the α -axis they will enhance each other, thus enabling a 1D search on the accumulated α -axis.

In the example the following data and values were used: (a) A data set of 100 000 points, flown as one strip with an approximate point density of 8 points/m². The number of multiple echoes in the vegetation areas were estimated to be 30% of the total number of echoes. (b) No approximate value

was given for α , i.e., the power line could take any direction, 0–180°. The half-circle was divided in 400 discrete steps. (c) d had a range of 385 m and was divided in 0.25 m steps, which should be sufficient to separate the power lines.

The three steps are shown in Figs. 11–16. Only a small part of the strip is shown in the figures.

4. Discussion

The usefulness of airborne laser scanner systems has been shown by other authors in a number of applications where the generation of DEMs with traditional photogrammetric methods fail or become too expensive, e.g., DEMs over areas with dense

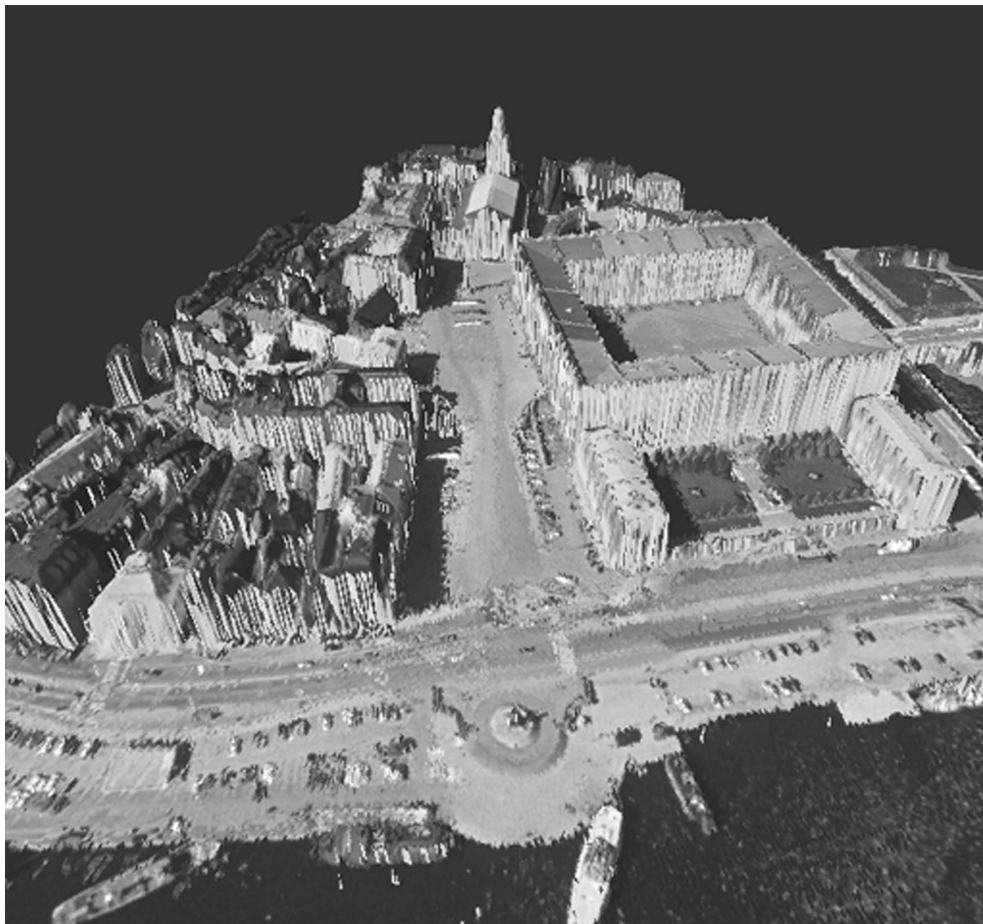


Fig. 17. LRF data overlaid with aerial image.

vegetation (Kraus and Pfeifer, 1998) or 3D City Models (Haala et al., 1997). High quality DEMs with sampling distances of 0.25–2 m are provided, depending on the application and system, within a short time limit.

The limitation of laser scanner systems lies in the fact that they are providing coordinates and coordinates only. On one hand, this allows fast and highly automated data processing. On the other hand, the interpretability of data is limited due to the fact that no object information is provided (Ackermann, 1996). Experience shows that it is, in many cases, impossible to interpret LRF data unless oriented images are available.

Automatic procedures for interpretation and classification of laser range data can be fairly successful for many applications using statistical classification methods. For a more general classification approach, other sources of information should be used in order to raise the success rate of the procedure. Such sources of information are reflectance data or multiple echoes from the LRF, images, existing 2D GIS databases, land-use maps, etc. (c.f. Fig. 17).

Therefore, if laser range data are to be used more extensively for mapping purposes, it is reasonable to believe that they need to be merged more closely with image information. This can be achieved either by using oriented images from photogrammetric image blocks, supplied directly from the same platform as the LRF data or from the LRF itself in the form of a reflectance image. This direction of development has also been confirmed by different system manu-

facturers now planning to present systems with both LRF and high quality image sensors. When such a system is carefully calibrated and tested, it will provide a highly self-contained mapping unit providing image and elevation data without any, or very limited, ground control.

Acknowledgements

Data and help provided by SAAB Survey Systems are highly appreciated.

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