Interpolation of high quality ground models from laser scanner data in forested areas

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ABSTRACT

Air-borne laser scanning is an applicable method to derive digital terrain models (DTMs) in wooded terrain. A considerable amount of the laser points are reflections on the tree tops (vegetation points). Thus, special filtering algorithms are required to obtain the ground surface. Earlier, we proposed to use iterative linear prediction. We review existing methods and compare them to our approach. A list of advantages and disadvantages of our method is presented, but this list has also validity for laser scanner data processing in general. The quality of the DTMs derived from laser scanner data and accuracy investigations are presented for two examples.

1 Introduction

The applications of DTMs are well known. Also for forested areas it can be of interest to have a DTM of high quality. Until now, this was not possible. Terrestrial tacheometry on one hand, is too expensive and takes too much time for recording the ground surface in a forest. Photogrammetry on the other hand, can (depending on visibility) only provide a surface through the tree tops. With the emerging of airborne laser scanning systems, the chance is given to obtain high quality DTMs in forested areas.

The laser beam from an air-borne laser scanner system can penetrate the tree tops and therefore a signal can be received, which originates from the ground surface. Of course not all laser points originate from reflections on the ground. Depending on the forest structure, time of flying (season) and tree type the penetration rate (i.e. the portion of ground points) can range from almost 100% to 0% [Rieger et al., 1999b]. Thus, laser scanner systems provide a point cloud, some of the points are ground points, others are so-called vegetation points. *The aim of this paper is to demonstrate the applicability of laser scanner data for the derivation of high quality DTMs in forested areas. It shall also be made clear, that it is worth using a sophisticated filtering method for this end.*

In this paper we will first present a review of the methods for laser scanner data evaluation, including the classification and interpolation algorithm we developed. A short comparison of the algorithms will be given. Following is a section on the performance of our algorithm. This section also includes passages valid for many different laser scanner filtering algorithms. In section 4 two examples will be presented in more detail. Results of accuracy investigations will be mentioned too. We conclude by presenting an outlook for our research activities.

2 Classification and interpolation of laser scanner data

2.1 Review of methods

At the Institute of Photogrammetry at the Stuttgart University the so-called morphological operator 'opening' has been applied for the task of evaluating laser scanner data [Kilian et al., 1996]. A window is moved over the data set. The lowest point in the window is considered to be a ground point. All points within a certain height bandwidth above this point are considered to be ground points as well. They are given a certain weight depending on the window size. This is repeated for several window sizes. The last step is the surface interpolation (approximation) under the consideration of the weights.

The TerraScan (a module of TerraModeller) filtering method is described in [TerraScan, 1999]. An XY–grid is laid over the whole data set. The size of this grid has to be specified. The lowest point of each mesh is considered to be a ground point. These points are triangulated which gives a first representation of the surface. The final surface is build iteratively by adding points to this triangulation. Points are accepted or rejected according to certain criterion. One criteria measures the height of a candidate point above the present surface, an other measures the angle between the surfaces with and without the candidate point. If certain threshold values are reached a point is inserted into the triangulation.

At the Institute of Photogrammetry and Remote Sensing at the University of Karlsruhe an other filtering method has been developed [Hansen and Vögtle, 1999]. They propose two methods. The first method proceeds by always taking the lowest point of a window which is systematically moved over the area of interest. For the second method the convex hull of the point cloud has to be derived first. The 'lower part' of the convex hull (in the form of a triangulation) is the first approximation of the terrain. Next, points are included into the ground surface, if they match certain criteria which measure the distance of a candidate point from the present surface.

Generally, the approaches to evaluate laser scanner data can be categorised in two ways.

- The algorithms in the first group perform only a classification. A surface model can be derived on the basis of the classification, i.e. as the last step.
- The algorithms in the other group derive a surface model. Classification of the points is done with respect to this surface.

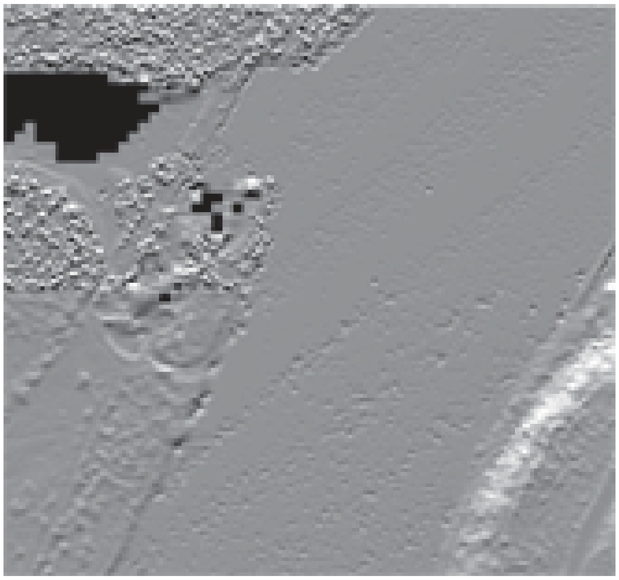

Figure 1: The data of this example – a last pulse flight – was provided in a grid. The shown view covers an area of 0.3km^2. The upper half shows the original data, the lower presents the filtered version. As it can be seen in this shading there are still vegetation structures (trees and bushes) in the data, though a filtering was performed in order to separate the ground points from the off-terrain points. In this data set negative errors occur, too. Notice the “holes” in the river surface. The flying direction in this example is north-east.

Some methods have a hierarchic approach to the surface interpolation or the classification step. Most approaches work iteratively, for interpolation as well as for classification. Filtering of measurement errors is not always performed. All methods have in common that they stress the lower points and assume that the higher points are vegetation (or more generally, off-terrain) points.

Often, the measurments are provided in a grid. To this end, a regular grid is generated and laid over the area of interest. At each position the height is interpolated from the neighbouring points (original points). This allows a considerable data reduction because only the heights need to be stored. However, one does not work with the original measurements any more. The methods for this interpolation are not documented, nevertheless it can be assumed that this process also favours the lower points. One solution is to take the height for each grid point from the height of the lowest original point inside a mesh centered on the grid point. For slanted terrain this leads to a systematic height error of $0.5w \tan\alpha$ (w: mesh width, $\tan\alpha$: terrain slope).

In fig. 1 a river scene is shown. It is a shading, the light source is in the north. The river flows in direction north-north-east, in the upper part a side arm can be seen. The water of this side arm is standing still (more or less). This might explain why no signal is received from the water surface (black area).

The upper part of fig. 1 shows the original data (to be more precise, a 1 meter grid) and the lower part presents the filtered version. It can be seen, that undesired structures are still in the data. The vegetation on the left river side is not eliminated completely. The data errors in the river (points below the river surface) are enlarged in the filtered version. This is due to the stressing of the lower points (which are in this case wrong).

2.2 Our method

In the method we proposed, linear prediction is used for the DTM interpolation. The error distribution of laser scanner heights with reference to the ground surface is no longer a normal distribution but a skew distribution with a strong bias towards off-terrain elevations. The points near the ground are considered to be normally distributed whereas the vegetation points have only positive residuals with reference to the ground. In the first interpolation step a rough surface approximation is determined. All points, whether ground points or vegetation points, have the same influence. Thus, the surface obtained runs in an averaging way between the ground points and the vegetation points. A modified weight function from robust adjustment is used to compute weights from residuals. Fig. 2 shows the residuals of the first interpolation step and superimposed the weight function. Each measurement (i.e. the height of each point) is given a weight according to its residual. These weights can be considered in the next interpolation step. Points with heigh weights attract the surface, points with low weights have less influence. Therefore, the interpolating surface runs nearer to the ground, disregarding the vegetation points. These vegetation points obtain a residual even higher than in the previous step. This process is called iterative robust interpolation. We use it to re-compute the surface and to classify all laser measurements into ground points versus off-terrain points (i.e. vegetation points in the case of wooded areas). The classification is done on the basis of a threshold value for the residuals. For a detailed description see [Kraus and Pfeifer, 1998] and [Pfeifer et al., 1999].

According to the characterisation of the methods mentioned before, this approach is an iterative approach, filtering of measurement errors is performed and the classification and interpolation are performed simultaneously. Of course it can also be applied to other data sources with an asymmetric distribution of gross errors.

3 Performance of the algorithm for laser data

In the meantime, we have gained lots of experience with this approach. Following is a list of advantages and deficiencies of the algorithm. Some of the points are not only valid for our approach but are valid for laser data processing in general. Thus, this section also includes some general laser scanner data characteristics.

Advantages:

1. The elevation model and the classification are performed in one step. For steep terrain this is an advantage. The classification is always performed relative to the ground surface. The ground surface may be distorted during the iteration steps, nevertheless the trend of the terrain will always be captured. This is an advantage over approaches which consider only the height of a point.
2. The algorithm can either work on original data or it can also be used to improve pre-classified data. An improvement of the classification perform by the company supplying the laser scanner data results in a higher quality of the digital terrain model derived from these ground points. However, if the points are given in an xy-grid, this is not exploited.

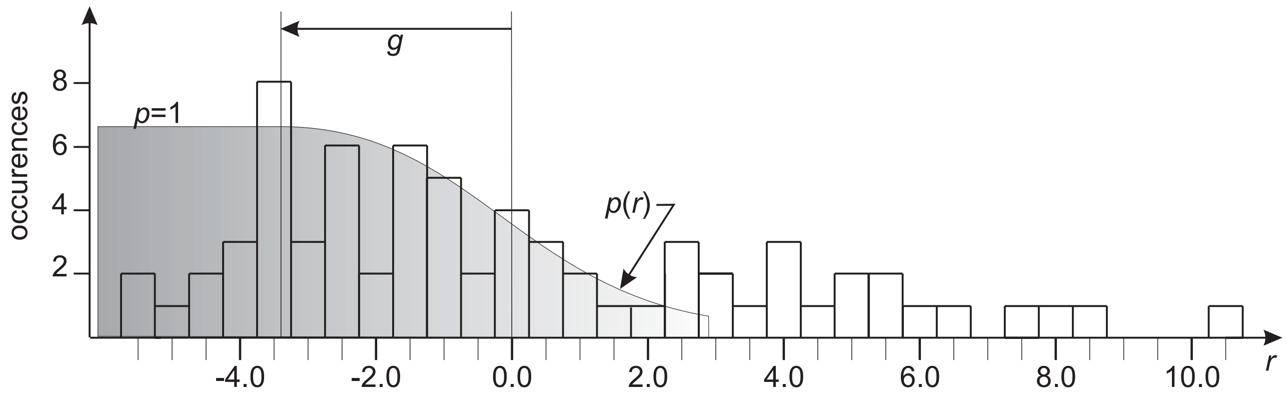

Figure 2: Residual distribution after the first interpolation step. The ground points are clustered at around -3m, whereas the vegetation points have residuals up to 10m. The weight function $p(r)$which is used to determine a weight for an observation (a z-measurement) is superimposed. Note, that the origin g of the weight function is negative and that the left branch of the weight function is identical to 1. Thus, ground points obtain higher weights than vegetation points.

3. High degree of automation. Mainly the initial setting of parameters and the end–inspection are left to the user.
4. There is the possibility to eliminate negative blunders as well. By an appropriate setting of the weight function negative errors can be given a lower weight and less influence, too. For this end, the weight function shown in figure 2 would decrease also for the left branch of the function. Of course this decrease need not be symmetrical to the right side.

   However, in order to maintain structures like break lines as good as possible, a soft filtering of negative errors is required. On the other hand this prevents the detection of negative blunders. Small edges are always blurred, whereas the general structure can be preserved.
5. The ground model has a very high quality. This is due to the interpolation process of linear prediction. On the other hand it is necessary to solve an equation system which has a dimension equal to the number of points. Therefore, this algorithm can only be applied patch-wise.

Deficiencies:

1. There is still interactive post processing required:

   Dense bush groups of larger size with very low penetration rate cannot be detected. Thus, a manual inspection with the help of digital ortho photos and/or other data sources is still necessary. Depending on the time of flying and the type of tree, the penetration rate can be as low as 0%. Dense deciduous trees during summer time or young densely planted conifer trees can reflect all laser rays in the tree tops [Rieger et al., 1999b] and [Rieger et al., 1999a]. If this occurs for larger areas, laser scanning is not an applicable method.

   Usually very large buildings are not eliminated. The situation corresponds to the point just mentioned. In such a case another data source like a cadastral map (or again the digital ortho photo) are necessary to detect and/or eliminate such artefacts. On the other hand, smaller buildings but also bridges are eliminated. It depends on the purpose of the project, if this is an advantage or not.
2. Negative errors occur, too. By this we mean laser points which are "measured" below the terrain. Because the algorithm puts more emphasise on the lower points, these are usually classified as ground points. This leads to a (topsyturvy) cone like pattern in the surface model, where the peak is at the negative error and the basis of the cone is on the actual ground surface. One source for these errors can be multi-path reflections. We observed such blunders in water areas as well as in urban areas. In water areas (fig. 1) we observed a number of neighbouring points (ca. 4) in a scan below the surface. They are between 0.5m and 2m under "ground" (i.e. the water surface). As all approaches stress the lower points, this behaviour is common to all approaches.

   Generally, structures above the local mean surface (e.g. embankments) appear smaller, structures below the mean surface (e.g. ditches) are enlarged. This can lead to a shift of terrain features.
3. There is no consideration of break lines in the terrain. Thus the edges of an embankment (or similar terrain features) are usually blurred.
4. For our algorithm the setting of the parameters is rather sophisticated, depending on the parameter setting negative blunders may be stressed
5. The computation times are rather long. Compared to simpler algorithms this approach requires considerably more computation time. However, as the process runs automatically, once the parameters are set, this is less of a problem. Furthermore, the increase in the quality of the DTM justifies this additional effort.

The first three deficiencies are general problems of laser scanner data evaluation. They also apply to grid generation mechanisms, especially if they favour lower points. Solutions need to be found in these areas in order to speed up the processing of laser scanner data. For a high quality of the final DTM either break lines are necessary, or the point density has to be very high (1 point per m^2).

4 Examples

In the meantime a considerable amount of experience has been gained in the processing of laser scanner data and the

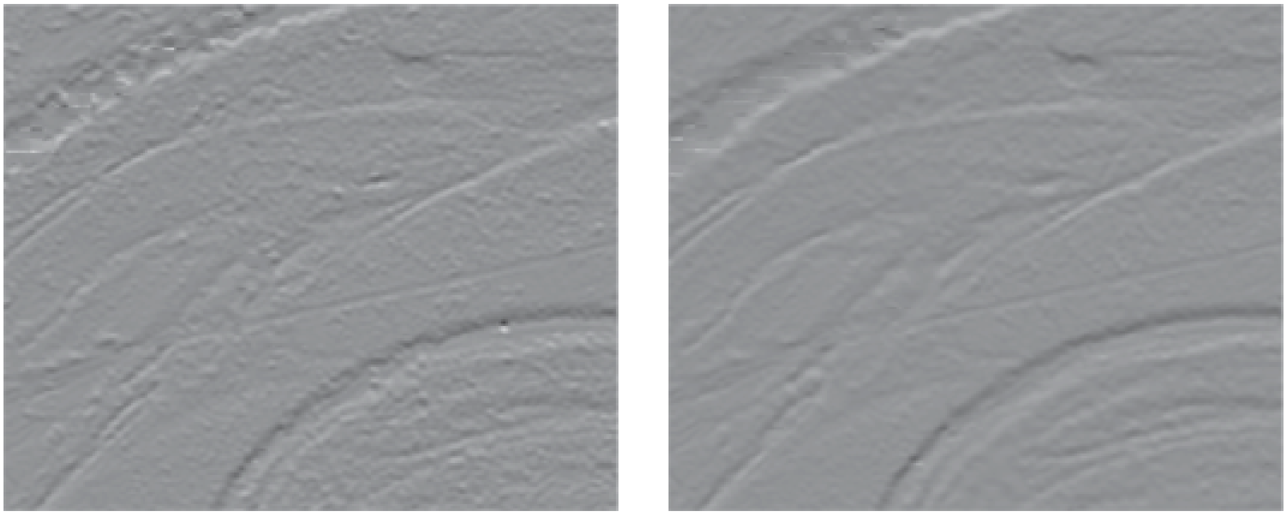

Figure 3: Shaded views of pre-filtered data and enhanced filtering. The area of this example is 480m×420m.

application of this algorithm. We have worked on several laser scanner data projects. These include urban areas, river scenery (riparian forests), hilly forested areas and forest enterprise areas with a very inhomogeneous tree structure. The data of this examples has been captured in the years 1998 and 1999 with different laser scanner systems. The areas of these examples range from a few to 100 km^2. The point density is between 0.1 and 9 points per m^2.

Two examples will be presented in more detail.

4.1 River Scenery

This project covers an area of $45km^2$. The area is rather flat, it is a riparian forest. The data was captured by TopoSys. The original laser points were used to interpolate a 1m-grid. The point density of the original points is 9 points per m^2. The time of flying was april, the foliage was well developed. The last pulse was recorded.

This data has also been filtered by TopoSys. The filtering can be seen in fig. 3, left part (and in fig. 1, lower part). In comparison the right part of fig. 3 shows the result of our filter process. Our filtering process is based on the filtered 1m-grid. The small vegetation structures are eliminated while the geomorphological detail is preserved. As it can be seen in fig. 1 points were measured on the water surface as well. The filtered TopoSys data has roughly two thirds of the primary 1m-grid. Another sixth part was eliminated by our filtering method. Thus the overall penetration rate is about 50% or below. To make a more precise statement on this point it would be necessary to know more about the interpolation process which is used to generate the 1m-grid.

Accuracy studies were conducted for this project as well. Along an embankment 60 points with an average distance of 280m were checked. These check points were placed along the edge of the embankment, which is free of vegetation. The r.m.s.e. of the DTM according to this reference points is ±27cm. However, the mean difference is around +20cm which indicates that the DTM from laser scanner data is below the 'real' surface. This systematic height difference comes from the grid generation mechanism and the application of our filter algorithm which narrow the features above the mean terrain (see point 2 in the deficiencies list). Another 104 points were randomly distributed over the terrain. The accuracy of the laser DTM according to these points is ±26cm.

4.2 Rosalia

The University of Agricultural Sciences owns a forest enterprise in the Rosalia range, south of Vienna, Austria. For an area of $5km^2$ the laser scanner data of a first pulse flight by TopoSys has been processed. The point density is 9 points per m^2, resulting in a 1m-grid. Flights were performed during winter time and summer time. As it can be seen in fig. 4 deciduous trees as well as conifers are planted in the area.

Fig. 4 shows the DTM from the original data. The vegetation points and other off-terrain points are still in the data. (Note the buildings near the left image border.) This DTM was generated with a the data of a summer flight. No filtering was performed. The figure shows a perspective view with the ortho photo draped over the terrain. The width of the area is approximately 200m.

In fig. 5 the same perspective is shown. A filtering with our algorithm was performed to obtain the ground model. The data source for the application of our alorithm was a winter, last pulse flight. In fig. 6 the data is shown, no filtering was performed. The conifers can still be seen, while the deciduous trees are not in the data because of the lack of foliage. In both figures the shading is draped over the terrain. The break lines (street borders, bottom line of the valley) are clearly visible in the terrain, the buildings are eliminated. The penetration rate is 60%. As it can be seen in the figure, not all bushes could be eliminated completely. As mentioned previously the laser beam often cannot penetrate dense bush structures. However, stronger filtering would have resulted in loss of other geomorphological details.

Accuracy investigation were conducted for this area as well. A total number of 2300 points were measured manually. The mean error of these points in each co-ordinate is ±5cm. The average terrain slope in this area is 40%. The r.m.s.e. of the DTM heights with reference to these check points is ±66cm. If the check points are grouped according to terrain slope, the connection between slope and accuracy can be derived. For flat areas (0% – 10%) the r.m.s.e. is ±20cm, growing linearly up to ±1.1m for 65% slope and more for even steeper areas.

Figure 4: Summer first pulse model with an ortho photo draped over it

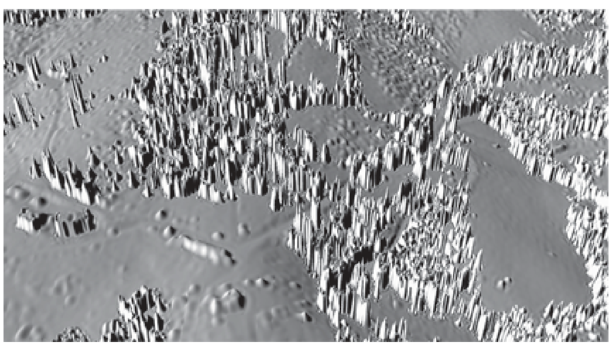

Figure 6: Winter last pulse model, no filtering was performed for this model

This result can be improved significantly, if a systematic error is removed from the DTM. For this end we compared the break lines of the DTM ([Rieger et al., 1999b]) with the check points, which were measured manually along the same break lines. A systematic shift between the check points and the detected lines in the xy-plane could be observed. According to this investigation the error in the geo-referencing is about 2m in the xy-plane. After shifting the DTM the accuracy results are significantly better: for 0%–10% slope an accuracy of ±16cm, for 65% slope an accuracy of ±50cm. On one hand, this indicates how important a correct geo-referencing of the data is. On the other hand, it shows that it is not enough to have only one GPS reference station, as it was the case in this example.

4.3 Conclusion from the examples

There are a number of conclusions to be drawn from the examples presented and the overall experience we gained with the processing of laser scanner data.

- The quality of the ground model can be increased significantly by applying a qualified filtering method. The filtering performed by the companies can be seen as a pre-filtering. There is still a considerable amount of manual work in the processing.
- The height accuracy of laser scanner data in flat terrain is around 20cm. It deteriorates with increasing terrain slope. The accuracy of ±0.5m is reached between 60% and 70% terrain slope. If the geo-referencing is not correct, the accuracy becomes worse, especially for mountainous terrain. This result is slightly better than our earlier investigations [Kraus et al., 1997] and [Kraus and Pfeifer, 1998].
- It is not enough to use only one GPS reference station to perform the geo-referencing of the data. One solution, which does not need more GPS reference stations, is a block adjustment with height and plane control points of the local co-ordinate system. Original laser points (no grid-points) need to be identified, which match these control points. The parameters of a spatial similarity transformation can be obtained by performing the block adjustment. These parameters can be used to either transform the original laser points or the grid points into the local co-ordinate system.
- A higher point density does not automatically yield a higher accuracy of the DTM. However, geomorphological detail can be captured much better with a higher point density. This results in an increase of accuracy at break lines or other features. Nevertheless, the position of these features can be shifted because of the filtering process.

5 Outlook

In order to increase the amount of automation in the processing and evaluation of laser scanner data the extraction of break lines will be necessary. There are

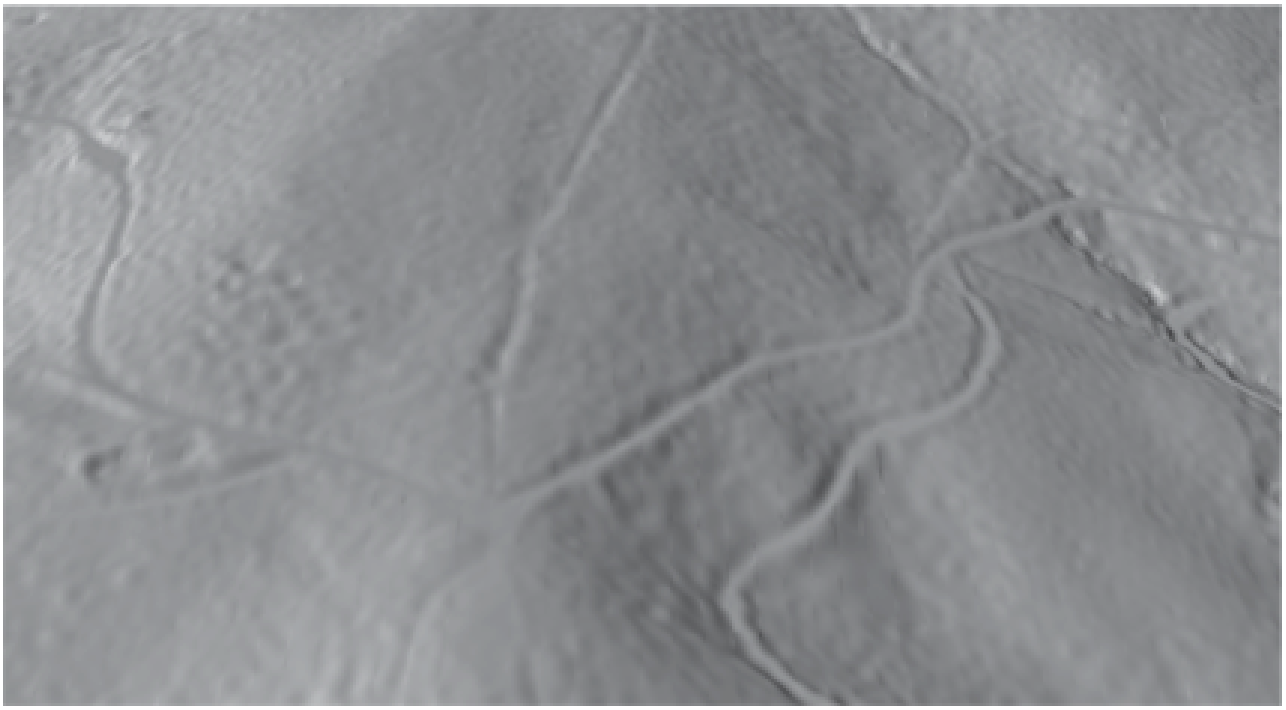

Figure 5: Ground model with shading, the break lines are maintained

different approaches for this end [Rieger et al., 1999b] and [Wild and Krzystek, 1996].

The automatic elimination of negative blunders is not operational at the moment. In water areas it is possible to apply the algorithm with a weight function mirrored to the one shown in fig. 2.

Another aspect we are currently working in is the derivation of a DTM in the city. To this end we are using a 0.5m-grid. Negative blunders can also be found in this data set.

Implementation work as well as theoretical extensions to the overall process of laser scanner data processing are necessary. The use of other data sources (e.g. aerial images) as well as the derivation of additional surface information from laser scanner data are one area of research. Though the degree of automation is very high, it is our aim to further increase the automation in laser scanner data processing for the derivation of high quality DTMs.

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