Technical Report

An improved morphological filter for selecting relief points from a LIDAR point cloud in steep areas with dense vegetation

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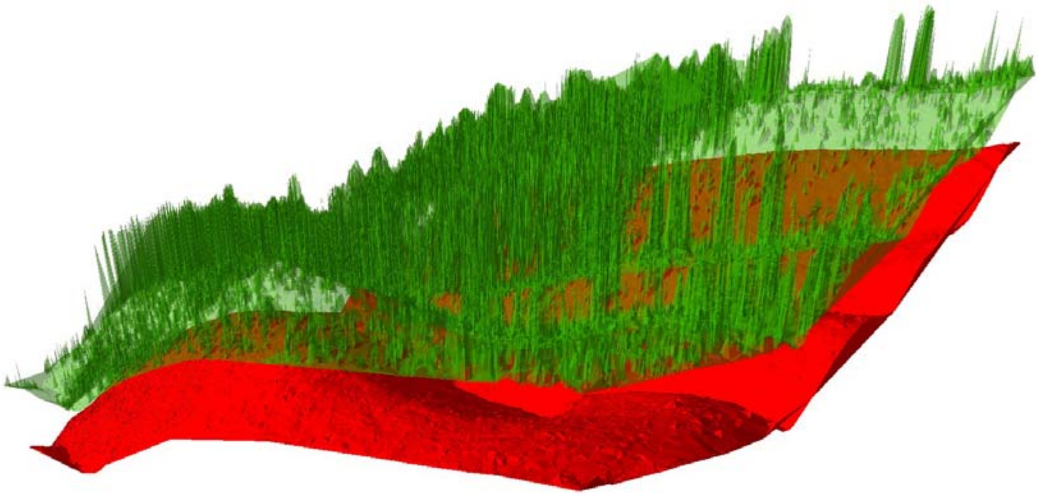

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1. Introduction

Airborne LIDAR is a remote-sensing technique that provides very dense and accurate spatial data in the form of an (unorganized) cloud of points. This kind of data usually contains a certain level of noise, which is the consequence of measurement characteristics. Each laser shot, emitted from the flying platform, can produce more than one echo from reflecting surfaces. The coordinates of these reflecting “points”, also called targets, are determined. Multiple echoes from a single laser shot might occur because of obstacles in the way of the beam towards the ground. The measurement equipment usually records the first and the last received echo signal (Pfeifer et al., 2003). In the case one wanted to produce a digital elevation model (DEM) the last echo data could be used in a first instance. The problem is that the last echo data do not necessary contain only the ground hits, because in case of dense vegetation the laser beam could not penetrate the vegetation. Therefore, “raw” LIDAR data has to be filtered before its actual use in a specific DEM application.

There are many filtering techniques (Kraus et al., 1998). Some of the most important LIDAR companies have developed their own instruments and also their own data processing software but general public is not familiar with algorithms they use. On the other hand, filtering algorithms have been developed parallel by some academic institutions. Two algorithms, which have been often used in the recent time, are morphologic filter (Vosselman, 2000) and robust interpolation (Kraus et al., 1998). Morphologic filter is very simple and very efficient in areas with small elevation differences. On the other hand, one should expect problems with areas with steep slopes and very dense vegetation, because the morphologic filter then hardly differentiates between ground and vegetation points. Robust interpolation is more efficient than morphologic filter in steep slopes covered by forest. However, robust interpolation works slower, because it works in multiple iterations. Additionally, it has many free parameters.

Within this study we follow three aims.

- Define a new method that also uses the first echo (also called first pulse) data for the filtering. This is rarely done, although it also contains information on the relief.
- Define a new method that is simple, e.g. comparable in its complexity to the morphological filter.
- Define a method that works for steep forested areas. In these areas existing filter algorithms still have problems.

Therefore, we decided to improve the morphologic filter. We have improved its efficiency in steep areas with dense vegetation by using the data of the first echo. In the next chapter some background on morphological filtering will be presented. Chapter 3 presents the new algorithm and chapter 4 a case study. In chapter 5 a short assessment of the method is performed and the report ends with conclusions.

2. Research background

A few facts about the classic morphologic filter should be stated in order to explain the improvements. The morphologic filter is very rough and effective because its simplicity – it compares an elevation difference between two points with the maximum allowed elevation difference regarding the horizontal distance between them (Vosselman, 2000). The kernel of the filter is a cone surface, which can be generated in three possible ways: by synthetic function, by preserving important terrain features regarding the reference data or by minimizing classification errors. For the last procedure a reference data set is necessary. Every point of the recorded data is then checked if it lies above or beneath the cone. A point is rejected as a ground point if at least one point in its neighbourhood is situated below the cone (Figure 1).

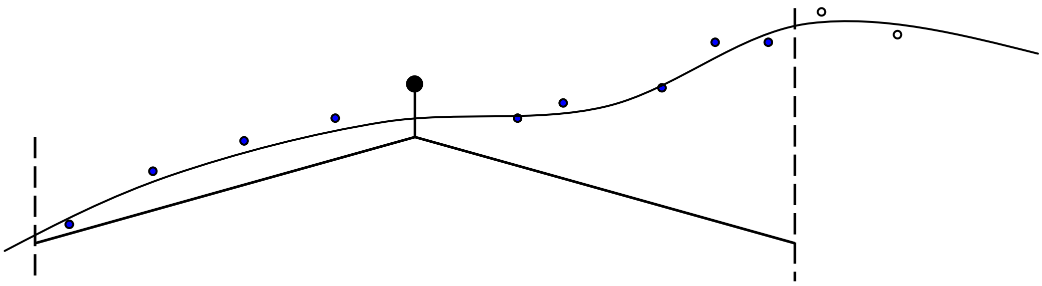

Figure 1: A neighbourhood is determined for every recorded point (blue points are in the neighbourhood of the black point). The elevation difference towards other points inside the neighbourhood presented with the dashed lines is compared with the maximum allowed elevation difference regarding the distance. The point is rejected as ground point if at least one point of the neighbourhood is below the cone.

The simplicity of the morphologic filter is the reason for its effectiveness in the areas with small elevation differences. On the other hand, the algorithm is not so successful in areas with steep slopes, especially if very dense vegetation is present. The filter has difficulties to distinguish among ground and vegetation points, because elevation differences between ground points become similar to vegetation differences between ground and vegetation points. Therefore, a lot of mistakes of first or second type can be made (Figure 2) – if a small slope is chosen, then many vegetation points are accepted as ground points (first type error). If a large slope is chosen, then many ground points are rejected (second type error).

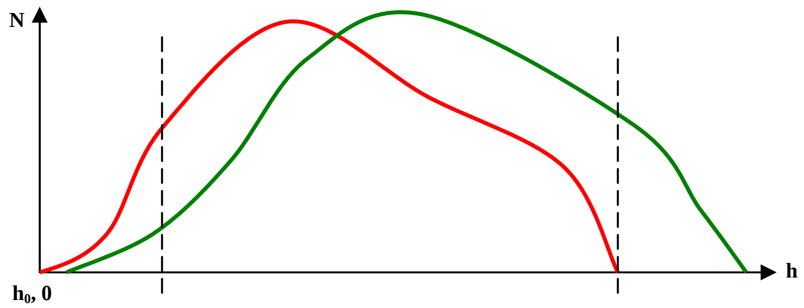

Figure 2: Choosing the appropriate filter kernel is problematic because elevation histograms of vegetation (green line) and terrain (red line) are similar (schematic image), which can lead into errors of either first or second type. Note that the figure shows absolute heights whereas morphological filtering works on slopes.

The main algorithm weakness is its isotropy – the allowed elevation difference is the same in all directions. It does not matter if the processed point is situated down or up the slope, which obviously makes no sense – the expected elevation differences should be:

- negative down the slope,
- zero perpendicular to the slope and
- positive up the slope.

The morphologic filter is based on the assumption that the data trend surface is a horizontal plane and the real relief is presented with anomalies on the horizontal trend surface. Therefore, morphologic filter is easily improved by a use of a "better" trend surface instead of the horizontal plane. The cone is than applied to the new trend surface, which means that the allowed elevation differences depend on direction – anisotropic filter. A good trend surface is required in order to make this approach work. It is possible to extract a trend from the raw data or even from external data like an existing DEM, which can be of a coarser resolution. Furthermore, the cone that is applied to the trend surface has to be defined – it is possible to define it similar as in the classic morphologic algorithm but it is better that it automatically adopts the trend surface.

3. The new algorithm

3.1 Defining the trend surface from raw data

A regularly distributed grid approach was used in order to define an appropriate trend surface because an accurate global trend is analytically too hard to set (at least in the case of the rough relief). Therefore, a first order trend surface (plane) is generated within every grid cell, which should be approximately as large as an average crown. This value is a lower limit and can be used if the point density is much higher than one point per tree crown. One might expect problems on the border between the grid areas because local trend surfaces do not merge into a continuous surface, but these gaps are very small with dense and regularly distributed data. A local trend surfaces was defined in two steps:

- the first echo data are used in the first step,
- the trend is readjusted after the analysis of residuals of the first step trend surface.

Figure 3: One can predict the geomorphology from vegetation. The figure shows first echo data.

The idea of using data of the first echo for selecting ground points is innovative. The question that stands out is obvious: “How can be data of the first echo used to generate a DEM?” One can predict the morphology of terrain below the vegetation when a forest is observed from a large distance, because the canopy elevation does not change rapidly (Figure 3). Therefore, an assumption can be made that the forest structure is homogeneous within a single cell, which leads to the stationary difference between vegetation trend and ground trend. Therefore, a horizontal surface through the data of the first and the last echo is interpolated for every grid cell. The elevation difference between these two surfaces is a low estimate (a lower bound) for the maximum tree height in the cell. This value is used as a threshold above the data of last echo trend (Figure 4). The actual threshold is set by multiplying the difference with a factor (real value between zero and one) in order to retain points that can be rejected as ground points to soon.

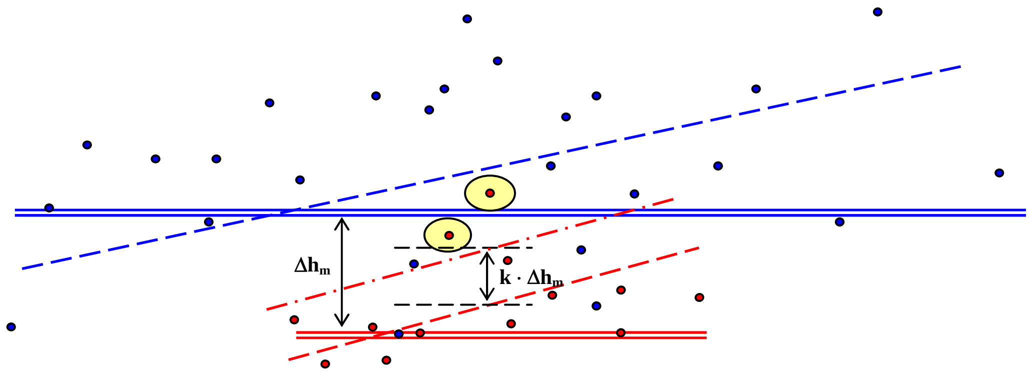

Figure 4: Last echo points (red dots), first echo points (blue dots), red double line (horizontal surface of last echo data), blue double line (horizontal surface of first echo data), red dash line (trend surface of last echo data), blue dash line (trend surface of first echo data), red dash-dot line (threshold), dots marked with yellow are above threshold and that is why they are excluded.

The computation of the trend surface is performed by adjustment. The trend surface is defined as:

$$z - a \cdot x_i - b \cdot y_i - d = 0$$

where x_i, y_i are the horizontal coordinates of a point i (on n points) and a,b,d are coefficients of the trend plane, which can be defined by Gauss-Mark model:

$$\begin{bmatrix} v_1 \\ v_2 \\ \\ v_n \end{bmatrix} + \begin{bmatrix} x_1 & y_1 & 1 \\ x_2 & y_2 & 1 \\ & & \\ x_n & y_n & 1 \end{bmatrix} \cdot \begin{bmatrix} a \\ b \\ d \end{bmatrix} = \begin{bmatrix} z_1 \\ z_2 \\ \\ z_n \end{bmatrix} \quad \text{or} \quad v + B \cdot \Delta = f$$

where v is a vector of residuals, B is a matrix observation equations (first derivates), Δ is a vector of unknown values and f is a vector of observation values. The vector of unknown values is determined by solving normalized system. It is assumed that all the observations have the same accuracy and that they are not correlated. Last echo points that are above the threshold derived from first and last point echo are recognized as vegetation points.

The last echo points that passed first step are used for a new trend surface computation with Gauss-Mark model. The points from the closest neighbour areas are also included in the trend determination because a lot of vegetation points are still present after the first step filtering and using neighbour areas provides more generalized trend, which is more probable. It is also more probable that points below it are ground points than points above the trend. Therefore, all the points that are below the threshold, which is defined by distribution parameters (derived from standard deviation of the residuals to the trend surface), are accepted as ground points (Figure 5). Moreover, if standard deviation is small enough (regarding the accuracy of the measurements), all the points are accepted.

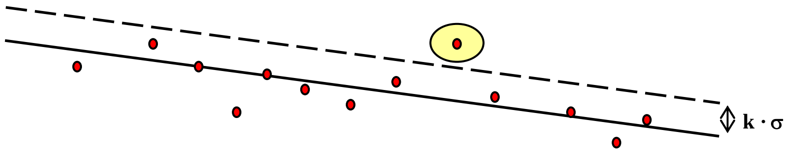

Figure 5: Threshold (upper dashed line) above trend (solid line)

3.2 Defining the filter kernel

After a satisfactory trend surface is computed a filter kernel (cone surface) has to be determined. The cone inclination is adapted to the curvature regarding the neighbourhood grid cells – a small inclination in the case of the flat trend and a large in the case of really curved trend (Figure 6).

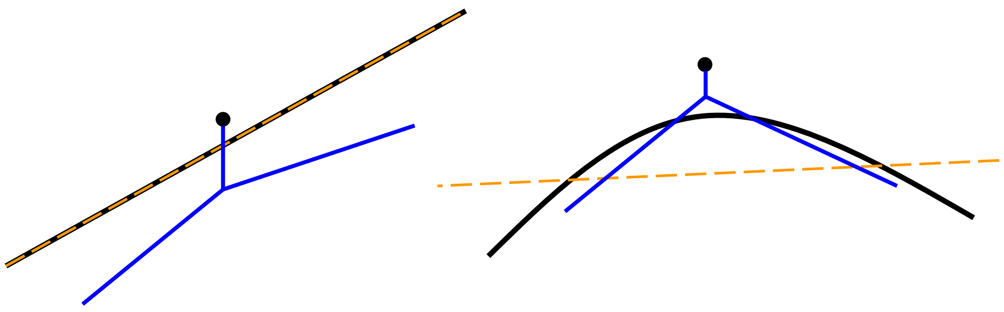

Figure 6: Possible structural elements of the filter (blue line), actual surface (black line), trend surface (orange dashed line).

Curvature, which is actually the second derivate of the surface, should be computed in two directions in order to be able to distinguish among all the important relief features (ridge, peak etc.). However, only the general curvature, which suited the purpose, was computed within this study with a simple but a quick method that is commonly used in commercial GIS software (Esri, 2005):

$$C = D + E,$$

where C stands for curvature, D and E are calculated with:

$$D = \frac{\frac{h_2 + h_3}{2} - h_0}{L^2}, \quad E = \frac{\frac{h_1 + h_4}{2} - h_0}{L^2},$$

where h_1–h_4 are average elevations of the grid cells; h_0 is the elevation of the currently processing cell and L is the resolution of the grid (Figure 7).

	h_1	
h_2	h_0	h_3
	h_4	

Figure 7: Computation of the curvature with a moving window.

The inclination of the cone should be adapted to the computed curvature. Maximum allowed distance (filter kernel) between point i and point j is then defined by:

$$H_j^{min}(d) = a \cdot x_j + b \cdot y_j + d + v_i - f(C) \cdot d - f(\alpha) \cdot \sqrt{2} \cdot \sigma$$

where $H_j^{min}(d)$ is maximum allowed elevation for point j that is for distance d away from point i, f(C) is the function that defines maximum slope, f(α) is confidential interval and σ is standard deviation of measurements. The filter is also presented in Figure 8.

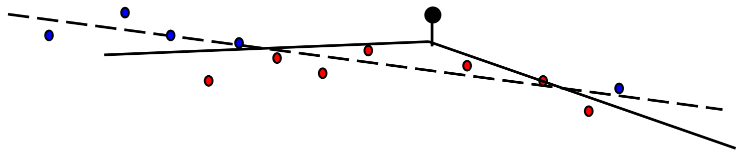

Figure 8: Structural element of the filter; black point is rejected because of its position regarding red points.

4. Case study

An area on 200 by 200 m was chosen for testing of the algorithm. Almost 400,000 points were reordered in this area, which means that the average point density equals approximately 10 points/m^2. The relief in the case study is very rough: the elevation difference between the highest and the lowest point is almost 100 m, it contains even slopes with inclination greater than 70 % - just for the illustration: this is as steep as the steepest ski slopes. The vegetation in the area also varies from sparse to extremely dense forest rich with undergrowth.

The algorithm is still in testing stage so the used algorithms were determined experimentally. Grid cells with size of 5 by 5 m were used for trend determination. The expected error of 0.3 m was assumed in measuring elevation differences. The difference between horizontal planes of the first and the last echo was multiplied with 0.8 in order to determine the filter threshold in the first step. Standard validation multiplied with 1.2 was used as a filter threshold in the second step of trend determination. The cone inclination was set as the sum of the constant 0.15 and the square of the grid cell curvature.

Figure 9 shows the tin from the first echo data, the last echo data, the data filtered after the first step, the data filtered after the second step and the final results containing “only” the relief points. It can bee seen that the vegetation really has a trend, which can be used for filtering purposes. Furthermore, the improvements can bee seen in all the filtering steps: the first step cuts the highest points by using vegetation data (60,070 points of the last echo data rejected), the second step produces satisfactory results for many applications in the majority of the area (18,487 points of the last echo data rejected) and the last step removes the rest of the noise in the area where trend surface was defined good (31,039 points of the last echo data rejected). 111,883 of all the 221479 points were accepted on the end as the relief points. The advantage of this algorithm is preserving ground points because the visual analysis of the results has revealed that the majority of the relief points were accepted. On the other hand, some vegetation points have not been filtered out of the results because of very dense vegetation.

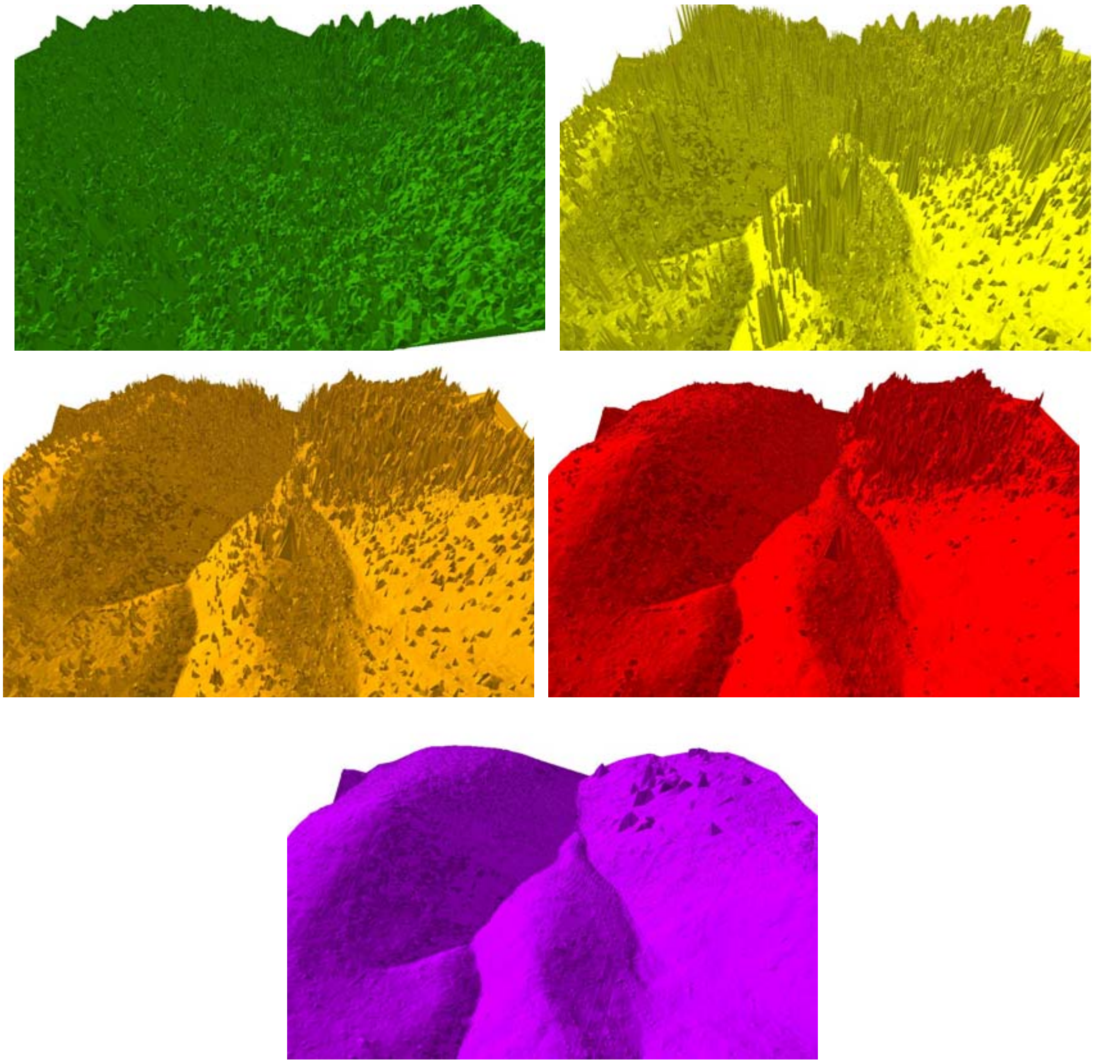

Figure 9: The first echo data (green), the last echo data (yellow), the first step results (orange), the second step results (red), the final results (purple; some vegetation points that were not rejected can be seen on the right side).

5. Assessment

The algorithm was tested in Octave (Octave, 2004), which is General public licence software. The filtering time for the area of 200 by 200 m with more than 220,000 points in the last echo file and approximately 170,000 points in the first echo file took approximately 5 min on relatively strong laptop (Pentium Centrino 1.6).

There are unfortunately not many data to evaluate the results. The best elevation data that were available for our study are the elevation contours from in the scale of 1:5000. Contours generated from filtered LIDAR measurements in general follow the main geomorphology of the relief presented with map elevation contours. Furthermore, the LIDAR contours provide more information of the relief as map contours (Figure 9). Some filter errors are seen in the upper right part of the image.

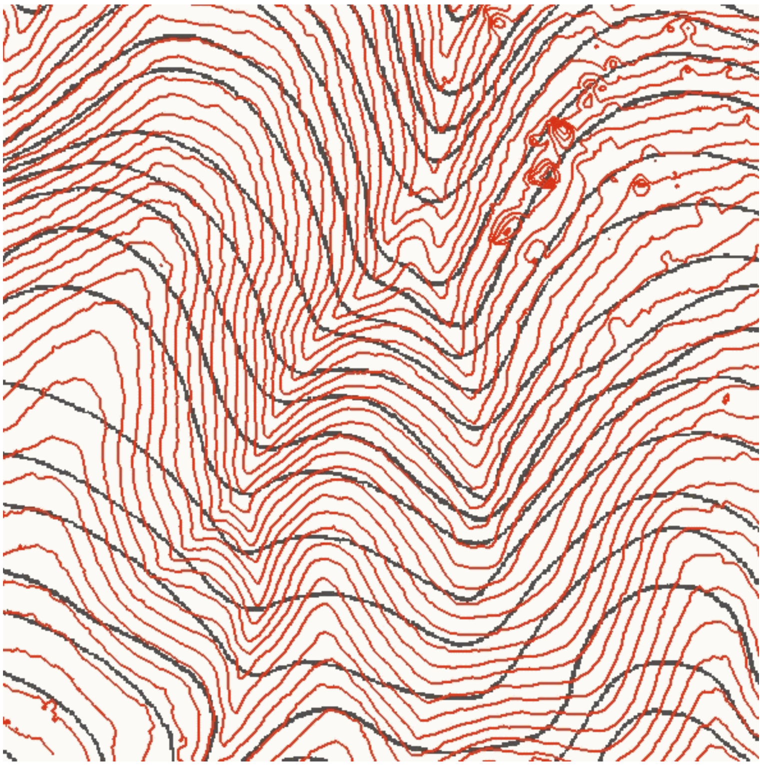

Figure 10: The comparison between elevation contours generated with LIDAR (red) and contours from a map in the scale of 1:5000 (grey; source TTN5 2004, © Surveying and Mapping Authority of the Republic of Slovenia); LIDAR contours provide more information about the relief.

6. Conclusion

The first results are very promising. The comparison with the classical geomorphological filter has shown the advantage of the new approach – the surface is better defined by preserving all the important relief points and by removing most of vegetation at the same time. However, a problem of filtering relief points in the very dense vegetation areas remains because it is impossible to make a satisfactory relief trend surface when there are too few ground points recorded – we could not even distinguish among vegetation and relief points during the visual analysis. Therefore, external data would provide a significant improvement – in the case the problematic are is flat, the classical morphological filter would be used. Even a better solution would be the use of an external DEM (of a coarser resolution), which is an excellent trend surface, thus only the third step of the described filter would be used.

The trend surface can be defined with a higher order polynomial (e.g. a hyperboloid instead of a plane), which would remove discontinuity gaps among the grid cells. However, the tests have showed that the discontinuity can be neglected and furthermore, the first order trend is computed much faster than a higher order polynomial trend. The curvature was used in order to adapt the filter kernel to the data, which means that the important skeleton features are accepted. If only a constant filter kernel were used, many points in the relief skeleton area would not be accepted as the relief points.

Argued from a mathematical point of view the changing between continuous and discrete objects within the whole process can be questioned. However, this approach works satisfactory in practise. It was shown that when a satisfactory trend is present it is possible to use the same idea as the classical morphological filter introduced. However, our approach is more universal, which gives it the possibility to use it successfully also in steep areas covered with vegetation.

Returning to the three aims stated in the introduction the following conclusions are drawn.

- It is possible to use first echo data, but the first echo data was only used in the very first steps of processing. It is also argued that a trend surface estimation could be performed by using an existing DEM. There is no substantial gain achieved by using the first pulse data.
- The method is simple, and the parameters that need to be chosen are not more than for the classical morphological filter.
- The method was designed for steep forested areas and not tested on other surfaces. While the results are satisfactory for this type of landscape, the wider applicability of the proposed method was not checked. At the current state it is therefore suggested for use in specifically those areas.

Acknowledgements

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