SEGMENTATION BASED ROBUST INTERPOLATION – A NEW APPROACH TO LASER DATA FILTERING

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ABSTRACT:

With airborne laser scanning points are measured on the terrain surface, and on other objects as buildings and vegetation. With so-called filtering methods a classification of the points into terrain and object points is performed. In the literature two approaches – i.e. a general strategies for solving the problem – for filtering can be identified. The first work directly on the measured points and geometric criteria are used for the decision, if a point is on the ground or an object point. The methods from the second approach first segment the data and then make a classification based on segments. In this paper we present a new approach for filtering. It is a combination of both approaches, specifically exploiting their strengths. A filter method following this new approach is developed and demonstrated by examples.

1. INTRODUCTION

Nowadays, airborne laser scanning (ALS) is a widely used technology for topographic mapping. In the last decade, many methods have been developed for digital terrain model (DTM) generation and other topographic models, and a great variety of applications exists and was developed based on these models.

With ALS points are measured on objects between the sensor and the ground surface, depending on where the laser beam is reflected. As it can be reflected by power lines, vegetation leaves, house roofs, etc., many points do not lie on the ground surface. Classification of these points into ground and object (off-terrain) points is called *filtering*. This step is necessary for DTM generation, but also further reconstruction of topographic features (houses, power-lines, etc.) are often performed relative to the DTM, using a normalized surface model.

Most of the filtering algorithms consider points (or raster elements) as the smallest unit of the process. Therefore, these methods will be called *point based* in the following. All of points (or pixels) are investigated and labeled as object or terrain point, e.g. analyzing the slope between adjacent points. These filters do not consider points in groups but each point is treated individually. Another group of filters performs first a segmentation of the point cloud. Points are grouped into segments according to some homogeneity criterion. Therefore, these methods will be called *segmentation based* in the following. Rule based classification is applied to distinguish between terrain segments, e.g. considering the smoothness of the segments or the height difference to neighboring segments. An overview on filtering methods can be found in Section 2. In this section we also review segmentation methods applied to ALS data, independently of the filtering task.

In Section 3 we give a motivation for presenting a new approach for filtering. It is a combination of point based and segment based filtering, combining the strengths of both approaches. Therefore, results can be more reliable and less manual work has to be spent on checking the filtering results. Using this approach, it is additionally possible to make a clear distinction between fundamental characteristics of the data on the one hand and of the terrain model to be reconstructed on the other hand.

In Section 4 we explain our method of segmentation and describe a new filtering method, the segment based robust interpolation, following the paradigm developed in Section 3. In Section 5 examples are presented and conclusions are drawn in the last Section.

2. PREVIOUS WORK

2.1 Filtering of airborne laser scanning data

The first group of filters got its name from mathematical morphology (Haralick and Shapiro, 1992) and was used in photogrammetry e.g. by Weidner and Förstner, 1995. In morphological filtering (Vosselman, 2000) a structure element, describing admissible height differences depending on horizontal distance is used. The smaller the distance between a ground point and its neighboring points, the less height difference can be accepted between them. This structure element is placed at each point and off-terrain points are identified. The structure element itself can be determined from terrain training data or obtained from maximum terrain slope assumptions. Variants of the morphological filtering are described in Sithole and Vosselman, 2001, where the structure element depends on terrain shape. In Kilian et al, 1996, multiple structure elements are used in the morphological operation Opening, and Lohmann et al 2000, applies Erosion and Dilation to replace raster terrain elevations with the filtered elevations.

The second group of filters works progressively. Some points are identified as ground points first, and depending on those, more and more points are classified as ground points. Axelsson, 2000 uses the lowest points in large grid cells as the first ground points and a triangulation of the ground points identified so far as reference surface. For each triangle one additional ground point is determined by investigating the offsets of the not classified points in each triangle with the reference surface. (The offsets are the angles between the triangle face and the edges from the triangle vertices to the new point.) If a point is found with offsets below threshold values, the point is classified as ground point and the algorithm proceeds with the next triangle. In this way the triangulation is progressively densified. Hansen and Vögtle, 1999 describe a similar method with a different choice of starting points (lower part of the convex hull of the point sets) and different offset measures. In Sohn and

Dowman (2002) the progressive densification works first with a downward step, where points below the current triangulation are added, followed by the upward step, where one or more points above each triangle are added.

The third group of algorithms is based on a surface model through the entire point set that iteratively approaches the ground surface. A first surface model is used to calculate residuals from this surface model to the points. If the measured points lie above it, they have less influence on the shape of the surface in the next iteration, if they lie below, they have more influence. In Kraus and Pfeifer, 1998, linear prediction with individual point accuracies is used as surface model and a weight function from robust adjustment is used to compute weights based on the residuals. Points with high weights have small nugget components and therefore more influence on the run of the surface, point with small weight large nugget components and correspondingly less influence. In Pfeifer et al, 2001 this method has been embedded in a hierarchical approach to handle large buildings and reduce computation time. Elmqvist et al, 2001 use a snake-approach (Kaas et al, 1988) where the inner forces of the surface determine its stiffness and the external forces are a negative gravity. Iteration starts with a horizontal surface below all points that moves upwards to reach the point, but inner stiffness prevents it from reaching up to the points on vegetation or house roofs.

Finally, in the forth group of filters works on segments. In Sithole, 2005 a method is described that classifies the segments based on neighborhood height differences. Nardinocchi et al., 2003, apply a region growing technique based on height differences to get segments. The geometric and topographic description of the regions can be presented with two graphs, whereupon a set of rules, and on a further segmentation (based on the orientation of height gradients) the segments are classified into three main classes: terrain, buildings, and vegetation. The eCognition software is used on gridded data and segments are obtained from region growing. Lohmann and Jacobsen (2003) applies amongst others the compactness of these segments and the height difference to the neighboring segments, in order to detect different types of areas including terrain. In the method of Schiewe (2001) maximum and average gradients are used for classification of the data.

A comparison of the performance of some filter algorithms can be found in Sithole and Vosselman, 2004. The problems at break lines and step edges are especially mentioned there, which is one of the motivations for this work.

2.2 Segmentation of airborne laser scanning data

The purpose of this process is to group points with similar features into segments. In the field of laser scanning usually homogeneous regions (e.g. roof facets) are segmented. Many applications need this attribute information for surface analysis or model reconstruction, therefore numerous surface segmentation methods have been developed. This process is more important for close-range laser scanning applications, where mostly modeling is the main goal. For this reason, many of these methods are designed for close range measurements.

The first type of segmentations based on region growing. These approaches group points based on geometrical relations of neighborhood like height, slope or curvature difference. The method of Lee and Schenk, 2001, works on triangles and driven by a robust plane fitting. Roggero (2002) presented an approach that uses principal component analysis (PCA) on the generated feature space. Vögtle and Steinle (2003) segment 3D macro objects on the basis of an nDSM and detect buildings, vegetation and terrain objects on the basis of first/last pulse difference, height texture and shape parameters.

A clustering analysis based method is proposed by Filin (2002). It uses the position, the best fitting plane parameters, and height difference of neighboring points. Other variants of cluster analysis can be found in Hofmann (2004) and in Alharthy and Bethel (2004). Vosselman and Dijkman (2001) propose Hough-transformation to detect planar roof surfaces within the given building boundaries. In Hofmann et. al. (2002), amongst others the length/width rate of the segments (obtained with eCognition) and the height difference of the neighboring segments are used for building detection.

The results of the segmentation procedures are not independent from the point cloud density. By low density, the run of the implemented surface is smoother. The lack of spatial information (e.g. edges that loose their sharpness) makes difficult to find the segment borders. In case of high density, the run of the surface is more complex. The segmentation methods may produce too many small facets.

These algorithms assume 2.5D data, and therefore have raster data or TIN as data structures. Besides the advantages of this assumption, it means loss of information as well. In this form, it is difficult to handle overlapping surfaces (e.g. bridges) and take into account the real topological connection between the points.

3. MOTIVATION FOR A NEW APPROACH

The point based filter methods usually work well when object and terrain points are equally mixed. Typical filter errors are encountered, when this requirement is not met. Filter errors can be caused by extended buildings, e.g. low industrial complexes, where points in the middle of the roof are classified as terrain. On the other hand, too many bare earth points can be filtered out, especially at embankments and ridges, with the consequence that the sharpness of the edge is diminished.

The segment-based filters are typically designed for urban areas where many step edges can be found in the data. A shortcoming of these filters is that *no explicit surface* model is used in these filters. Additionally many segments may be generated in forested areas.

Because of filter deficiencies manual correction of filter errors is required. Point based filtering, for example, requires that areas near edges are manually checked and – if necessary edited – in order to correct filter errors.

Our overall aim is to increase automation and reliability of filter results. Therefore, a new approach combining *segmentation and filtering with a terrain model* is presented. While previous methods for terrain determination applied either filtering of sets of individual points, or segmentation and classification, this method is a combination of both. The first step of this new filtering approach is segmentation of the dataset. In the second step segments are classified either as ground or object segments. For this a method of surface model based filtering that operates on point groups instead of single points is developed.

The strength of the *segmentation-based* approach is that during segmentation only the homogeneity within the segment is guiding the grouping process. Therefore, segments reach exactly up to the break lines or jump edges. Advantages of using segments lie therefore in retaining break lines and the ground up to jump edges in urban areas. Because of this, this method is superior to filtering without grouping points into segments. The strength of the *point-based* approach is that an explicit surface model can be used. Describing the expected terrain surface with a dedicated model allows including terrain characterization in the filter process. Additionally, the point-based approaches have proven useful in the vegetated areas.

A common element in current point based and segmentation-based approaches are that they are so-called 2.5D methods. The 3rd dimension, the vertical, is assumed to be a function of the planimetric dimensions. For one planimetric position only one elevation may exist. While this is a correct representation of the terrain, excluding overhangs, it is not a correct representation of laser data. Because of different viewing angles in the area of overlapping strips points may be measured below a bridge and on the bridge surface. Likewise, points may be measured on (vertical) house walls. The 2.5D approach for data description is bound to introduce artifacts in the filtering stage.

In the new approach, a 3D method can be applied for segmentation and a 2.5D method for terrain description, making a clear distinction between these two steps.

4. SEGMENTATION BASED ROBUST INTERPOLATION

In the remainder of the paper a method for filtering airborne laser scanner data following the approach described in the previous Section is presented. First segmentation is performed. Then robust filtering is applied, but not for points as described in Section 2.1, but for segments.

4.1 Segmentation

The segmentation method applied and described here was originally developed for terrestrial laser scanner data. It is based on region growing and uses the n nearest neighbors of the points. These neighbors are used in the first preprocessing step to estimate the normal vector for each point. The region growing algorithm first picks randomly a seed point and then examines the n nearest neighboring points whether they fulfill certain criteria. An adjusting plane is estimated for the points of a segment. This plane is an orthogonal distance regression plane, since errors in all three coordinates are assumed. Points from the n nearest neighbors will be connected to the segment, if they fulfill three criteria:

- similarity of normal vectors (α),
- distance of candidate point to the adjusting plane (r),
- distance between current point and candidate point (d).

The first one (similarity of the normal vectors) means that the angle difference should be under a predefined parameter, using the normal vectors from the preprocessing step. The adjusting plane is recalculated after each accepted point, and its distance to the new candidate must be shorter than a predefined maximum value. The maximum distance of the current and the candidate point must be also below a certain value. Growing continues until no more points can be found fulfilling the criteria.

The process is affected by 4 parameters: n, α, r, and d. The density of the data can be accommodated by setting the number of neighbors and the maximum distance for accepting points. Points that are not part of any surfaces are individual segments. The practice shows that these are points of vegetation, vehicles, chimneys, power lines or other outliers.

The eigenvector/eigenvalue approach using the 2nd moments of the point coordinates are used for the plane adjustment. As the plane is not parameterized over the xy-plane, also vertical walls can be extracted. Likewise, stacked horizontal surfaces may form two segments where one is above the other. The matrix of moments can easily be updated after adding one point. This way the 3D content of the data is considered.

A result of the segmentation can be seen in Fig. 1. Different segments are shown in different color. The roofs are separated, and different parts of the terrain have been split at the respective break lines.

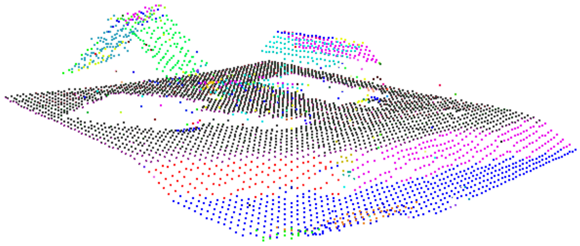

Figure 1: Segmentation of laser scanner data.

4.2 Robust interpolation for point groups

The method described in the following is an extension of the robust interpolation (Section 2.1). The input for the extended robust interpolation is the segmentation: points from segment j with their 3D coordinates (x_i, y_i, z_i). Also an indicator c^j can be given, specifying if this segment shall be subject to ground/object testing or not. In the latter case these points are considered to be ground beforehand. Additionally, a σ_0 a-priori has to be specified, which is the nominal laser measurement accuracy.

During the iterative ground surface determination, each point group has one weight w^j, which applies to all points within the segment. Initially this weight is set to one.

The robust interpolation for point group runs as follows:

1. A surface is interpolated considering the points with their current weight w^j.
2. The filter values r_i of the interpolation are computed and normalized by dividing with σ_0.
3. The filter values belonging to one segment are grouped and one representative filter value $r^{j\prime}$ is determined (averaging). Based on this value and a weight function for robust adjustment a new weight is set for the segment.
4. Test for iteration stop, if not continue with 1, otherwise classify segments as ground or off terrain on the current value of w^j.

For computing the surface moving least squares (MLS) with an order one polynomial (a plane) is used. A 2-dimensional weight function is used to give points near the interpolation position higher weights, reaching a value of zero at a certain range. In the interpolation the weight from MLS and w^j are multiplied. Segments with a large w^j therefore have a larger influence on the run of the surface. Segments with small or zero w^j have small or no influence. An example of the surface after the first iteration (equal weights for all points), is shown in Fig. 2.

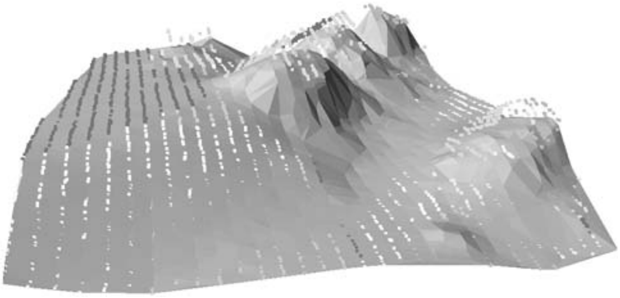

Figure 2: Original points with grey value according to segment, and MLS surface with equal weights for all points (1st iteration).

The filter value is the signed distance of the interpolated surface to the observed point. It is positive for points above the surface, negative otherwise. Dividing by the a-priori accuracy of the measurement system, $r_i' = r_i/\sigma_0$, yields a unit-less value. Depending on the distribution of measurement errors, points lying on the ground surface usually have values of r_i' from –2 to +2. Assuming normal distribution of the random measurement errors, 95% of the ground points fall into this category.

As a segment is either entirely a ground point segment, or entirely an object point segment, all normalized residuals of one group are analyzed together. The *representative normalized filter* value $r^{j\prime}$ from the segment to the surface is an average of all the single distances. However, the mean filter value is not the only one that can be taken. The median or any other quantile of the distribution, including the maximum positive filter value, can be used. In the examples below the 3rd quartile is taken as the average filter value.

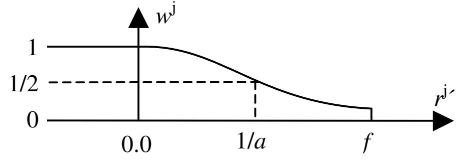

Figure 3: Parameters of the weight function.

The function to assign a weight for the segment is the standard weight function from robust adjustment with one modification (see Fig. 3). It is centred on the origin and drops from the maximum 1 to 0 for the right branch (positive filter values). The left branch is yields a weight of 1 for all (negative) filter values, i.e. segments with an average filter value below 0, "below the surface" will always have the maximum weight. The weight function is cut off at the right branch and set to zero for filter values above a certain size. For values of $r^{j\prime}$ between 0 and f, the weight function takes the form $w^j = 1/(1+(r^{j\prime}/a)^2)$, where a is the so-called half-weight filter value, the argument where the weight function yields the value 1/2.

Iterations shall be stopped, if all representative residuals are either small (e.g. within –2 and +2), or very big (e.g. higher than 10). This means that the segments have been classified into ground (low residual) and object (high positive residual). The values chosen depend on the method of computing the residual. If, for example, the mean value of the individual residuals is taken as the representative, the ground segments can be expected to have a representative residual of zero. After the last iteration the segments are classified as terrain or object, depending on the value w^j.

4.3 Discussion

Of course, this method builds on the robust interpolation as first proposed by Kraus, 1997. Therefore, the differences to this method will be discussed first. The most important difference is also the most obvious: the original method works on points, while this method works on groups of points. Kraus suggests using Kriging for the determination of the averaging surface and filter values, whereas here the simpler method of moving least squares is applied. Filtering with MLS is of lower quality, but calculation can be performed faster. Additionally, as the new proposed method works on groups of points, and not for each point individually, the quality of the single filter value is of less importance, compared to the representative normalized residual. Additionally, Kriging works especially well on very irregularly distributed data, where it is superior to MLS, but it is always a global interpolation method, which may cause problems when splitting large datasets for processing in smaller units. MLS can be defined to work locally, if the A 2-dimensional MLS weight function reaches zero for a certain range, which means that the steps of surface interpolation can be performed with less precautions for large areas. The new method also uses a simpler robust weight function. While the origin of the weight function is not centred at zero, but usually shifted to the negative (Kraus, 1997), the method proposed here centres the weight function always on the origin.

Using MLS allows setting a weight strictly to zero without obtaining singularities in the surface interpolation. Singularities are only obtained, if less than three points with weights larger than zero are in the range of the MLS weight function. This can easily be detected. Countermeasures can either be extending the weight function or not computing a surface height at this point and marking it already before the last iteration as object.

The method of robust interpolation was applied here to combine segmentation with filtering. All the surface based filter methods, e.g. the method of Elmqvist et al, 2001, can be easily used for the approach presented in Section 3. Also the progressive methods can be used, but with the difference that not one point, but an entire point group has to be checked for acceptance and surface (TIN) augmentation.

Using an indicator to specify if a point group shall not be subject to robust interpolation allows to consider additional information. Sources for this information can may topographic maps (land cover descriptions) or also the segment itself. The size of man-made structures has an upper limit, and vegetation – on the other hand – does not group together in large segments. Point groups with extents larger than this upper limit can therefore only be ground segments. If manual measurements are available, they can also be incorporated in this way.

The method of averaging the residuals and the weight function are governed by the nature of the data, especially their vertical distribution with reference to the terrain surface. Other data types may show symmetric errors, which can be accommodated by using a symmetric weight function. The a priori accuracy of the observation is a measurement of the ideal measurement, i.e. one that is performed on the surface of interest. Averaging the residuals cannot only be performed with the mean or quantiles as mentioned before, but also the quadratic mean (…) may be applied. This also depends on the segmentation results. If the

segmentation would be known to be free of error, always the largest residual could be used as representative. With the third quartile some imperfections of the segmentation are accepted.
The quality of the filtering depends largely on the quality of the segmentation. Over-segmentation is not harmful, but especially having segments with mixed object and terrain points leads to failure. As only under-segmentation has to be prevented, parameters of the segmentation algorithm can be set accordingly. Generally, different segmentation methods can be used. The one applied here was developed for terrestrial laser scanner data, which does not have the same characteristics as airborne laser scanner data. With improved segmentation methods the reliability of the filter results increases, too. Region growing based on normal vector similarity alone is interesting because the segments are not necessarily planar. Finally, in very rough terrain segments will become smaller and the method is reduced – more or less – to a point based method.

Depending on the density of points, the surface can either be evaluated at each point (suitable for lower density), or in a regular grid (suitable for higher density). In the latter case the surface obtained is defined by the bilinearly interpolated grid meshes, and the filter values are the distance from the appropriate grid mesh surface to the original point. Compared to the first technique of evaluating the surface in each point, this acts similar to a low pass filter. However, with high point density this effect remains small. The advantage is that the process runs faster.

5. EXPERIMENTS AND RESULTS

For the experiments, data of TopoSys II sensor has been used. It was captured at the ‘Salem’ test area, which is a rural area near the Lake Constance. The data set has been used with kind permission of TopoSys (Germany). Segmentation and filtering process have been performed on the last pulse echoes. The presented test data is not gridded, raw coordinates have been processed in order to prove the advantages of the 3D approach. In the 1st dataset, there are ~60000 points in a 140x150m area, which is almost 3points/m^2. This data is a thinned out version of the original data, with even higher density, but these points do not add more detail to the measured surfaces. Gridded data has been examined as well, where the grid size is 1m. However, in this paper only tests will be presented, which are based on not rasterised data.

Main goal of the segmentation is to produce homogenous segments. Therefore, the parameterization of the process aspires to provide approximately plane surfaces and the size and number of the fragments is less important. Since the point distribution is not equal in the flight direction and in the perpendicular direction, the n number of neighbors should be greater than by equally distributed data, in order to provide a neighborhood selection possibly in a circle around the examined point. In this case $n=24$. The similarity of normal vectors (α) has been chosen relative high (α=20°) with the aim of connecting points to the terrain segments that are near to edges. Distance of the candidate point to the adjusting plane (r) is 0,25m and distance between the current point and the candidate point (d) is set to 2m. The produced segments checked by visual inspection whether they contain mixture of points. 14% of the points belong to groups with less than 30 points and 51% of the points are in segments containing more than 1000 points per segment. Presented results are not edited manually.

In the robust filtering 4 iteration steps were carried out. The surface model is moving least squares with an adjusting plane (parameterized over XY). All points are used within a circle of 11m radius. Weight function has a halfweight of 1, 0.8, 0.6, 0.4 meter in the different iterations. The idea is to have a surface that gradually features more and more details and allows better fitting to terrainforms (e.g. break lines). The long range ensures that always ground points in the area of calculation, also for the larger houses. For the robust error removal the representative filter value per segment was the 66% quantile of the individual filter values. The weight function decreases from 7, to 5, to 3, to 2.5, and the range of the weight function, i.e. the place after which all the weights are set exactly to zero were 10.5, 7.5, 4.5 and 3.75, which is 1.5 times the halfweight. The a-priori accuracy of the points was set to 10cm. This means that a segment with a residual of 10cm has a normalized residual of 1. Finally, all segments with the weights larger than 0.5 were accepted. The segmented area and filtering result can be seen in figure 4. Some errors occurred through the “border effects”, but these are not shown in the figure.

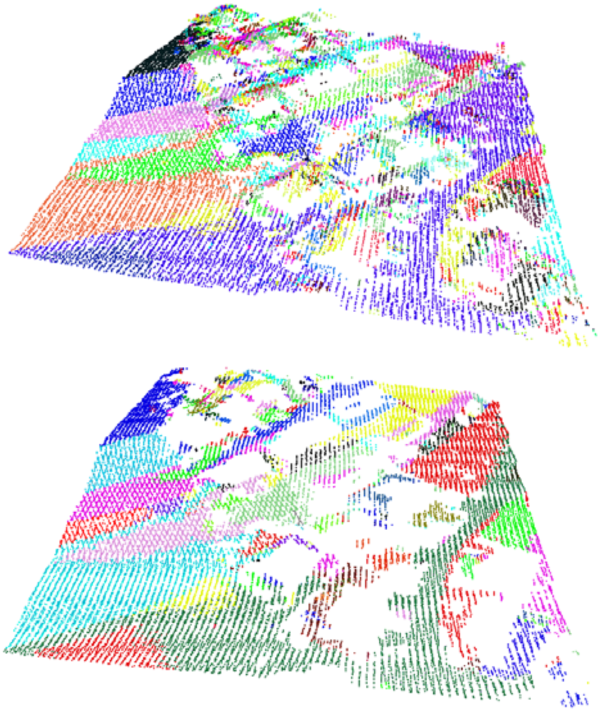

Figure 4. Segmented test area (above) and terrain segments after the segmentation based filtering.

6. CONCLUSIONS

In this paper a new approach for separating object points ground points in sets of airborne laser scanner data was presented. First, a segmentation of the dataset is performed. Then a filtering technique is applied that does not work on points, as most of the filter algorithms published so far, but on segments. A surface is interpolated initially from all points. Per segment a weight is determined and considered in the next iteration. Segments with lower weight have less influence on the run of the surface. This scheme is iterated until the object points are completely removed, i.e. have a weight of zero. The strengths of the method are i) no removal of ground points near edges, and ii) complete removal large objects.

The segmentation is performed with an algorithm that runs fully in 3D, i.e. no parameterization over the xy-plane (e.g. a triangulation or rasterization) is performed, something which is against the nature of ALS data anyway. The surface determination is a 2.5D step, which follows the nature of the terrain and therefore justified. Because of the surface following nature the method is not depending on the overall terrain slope.

The quality of the segmentation influences the quality of the filtering. While oversegmentation is not harmful, segments with mixtures of vegetation or houses and the ground make successful filtering impossible. Thus, parameters of the segmentation should be chosen to avoid oversampling and accept undersampling but insuring the homogeneity within the segment. The method may be applied together with other filters as well. After segmentation and segment based (robust) filtering, any other filter method can be applied. Especially if the segmentation has some errors (i.e. ground segments with vegetation), such a step can be performed.

In robust adjustment automatisation for setting of the halfweight values of the weight function is applied. The next step would be to apply this also to the segment based robust interpolation and to perform a numerical error analysis.

While combining segmentation and a terrain model in filtering, the method developed is still not using all information that can be obtained for ground detection in ALS data. *Parameters of the segments* (cmp. classification) on the one hand, and *explicit break line* information, on the other hand should be combined with segmentation and a *terrain model* to get the more accurate and reliable filter results.

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