Reconstruction of Building Ground Plans from Laser Scanner Data

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Abstract. Laser scanner data are a powerful data source for acquisition and update of high resolution topographic information. Current airborne laser scanning systems are able to acquire densities of up to 40 points per square meter. With this information topographic objects like buildings, trees, electricity lines, and the relief can be determined. The main problem is the classification and identification of these objects in the point cloud and their precise reconstruction.

In this paper we tackle the problem of delineating building ground plans from laser scanner point clouds. Starting point is a pre-processing step that distinguishes terrain and off-terrain points. Then, all connected off-terrain points are aggregated in a region growing process. These regions represent potential buildings. For them, in a third step, the outline is simplified. This is a generalization task, which has to take the characteristics of buildings into account to produce a meaningful 2D building shape. In the paper, these steps are described in detail. The focus lies on the different possibilities to generalize the building ground plans. We describe options for this generalization and especially focus of an approach using RANSAC followed by least squares adjustment.

INTRODUCTION AND STATE OF THE ART

Airborne laser scanner data describe the top surface of objects in terms of a point cloud in great detail. Today's airborne systems yield resolutions of 4 to 10 points per square meters; with helicopters also higher densities of up to 40 points per square meters can be achieved. These data sets provide an ideal data source for automatically detecting changes in the topography. Areas and objects of change can easily be detected by simply subtracting two data sets from different time instances. From an NMCA point of view changes relating to cadastral information are special importance. Typical change rates lie in the range of about 10% per year regarding the built-up structure. In order to detect them and update cadastre and digital maps, a high degree of automation is desired.

As already pointed out, for the automatic detection of the changes laser scanner data represent a very good source. In contrast to images, where the objects have to be interpreted first, before they can be compared with a previous situation, the 3D-point cloud can be compared with existing data on different levels: when laser data of earlier years are available, the two point clouds can be subtracted; if this is not the case, potential buildings in the point cloud can be identified and compared with the existing information in the cadastre. In order to identify potential buildings, methods to classify terrain and off-terrain laser points have been proposed (Kraus & Pfeifer, 2001, Abo Akel et al., 2004), the latter is also used in our study. Thus, change detection is relatively simple and easy to automate. The challenge is, however, the precise measurement and the reconstruction of the new and changed objects.

In the literature, some approaches for delineating buildings from laser scanner data have been reported. Most of them refer to the reconstruction of the 3D-geometry of buildings. From them, the outline of the ground plan can be determined. Maas & Vosselman (1999) present two approaches for this: the first is to use geometric moments to determine the main orientation parameters for gable roof buildings. For other kinds of buildings they propose to segment and intersect planar faces. In order to generalize the outline they use the direction of the ridge line as an approximation for the main direction of the building (modulo 90 degrees). This ridge line is determined as a horizontal intersection between roof faces. Gerke et al. (2001) use an recursive cut of rectangles from a minimum enclosing rectangle in order to fit a rectangular outline to the jagged building outline determined from laser scanning data. A similar approach has been realized by Dutter (2007). She starts with an MER and determines relevant deviations from the rectangle lines. This is done recursively, thus enabling different shapes of buildings like L, T or U-shaped outlines. Shan & Sampath (2007) use straight lines in the main direction of the buildings to approximate the shape and least squares adjustment for the adaptation to the original boundary points.

In cartography, methods for the simplification or generalization of building ground plans have been developed (e.g. Staufenbiel 1973, Lamy et al., 1999, Lee 1999, Sester, 2005). All try to eliminate too small edges, protrusions and insets of the buildings, while preserving and enhancing the properties of buildings like right angles or parallelism. These methods, however, cannot be directly transferred to the problem of simplifying outlines determined by laser scanner data analysis, as those outlines are only coarse approximations of the real building; they are typically jagged and potentially also spoiled with outliers.

EXTRACTION OF BUILDING CANDIDATES

Point classification

In this approach airborne laser scanner data is used to determine building ground plans. As a first step the buildings have to be detected in the data. To this end, we use the method of Abo Akel et al., (2004). The idea of their approach is to robustly interpolate the terrain from the measured points; points on buildings (or on trees) typically lie above points on the terrain. Thus an interpolation function is sought that tentatively only goes through the lowest point in a local area. In our case we do not use one areal polynomial, but a set of 1D-polynomials. In the approach, the whole ares is divided into parallel strips in x- and y-direction at a small distance of approx. 3m. The heights of the points of one strip are considered to depend only on the x-coordinate or the y-coordinate, respectively. A polynomial is fitted into the strips; we use polynomials of order 15 to 20. In the first calculation the weights of all points are the same, namely 1. The adjustment is iterated, whereas in each iteration new weights for the points are set: the weights of points below the polynomial function remain 1. The weights of the points above the polynomial function decrease with increasing height difference. The rationale behind this is to give the potential terrain points (the ones below the polynomial) a higher weight, and to decrease the influence of points above ground. With the new weights a new polynomial is determined. The calculation of the polynomial and the new weights is repeated until the changes of the polynomial is below a given threshold. Then, the polynomial tentatively goes through the terrain points.

Subsequently, the height of the points are compared with the polynomial. In our case we are only interested in buildings. So, only points above a certain threshold (in our case 2.5m) above the polynomial are classified as off-terrain. As there are polynomials in x- and y-direction every point is classified twice. Only the points that are classified as off-terrain twice are considered to be off-terrain, and thus building candidates. Our test data set has a point spacing of approx. 4 points per square meters. The result of the classification is given in Figure 1, left.

Segmentation

After all points have been classified into the classes terrain and off-terrain, points that belong to one building have to be identified. This is done by a segmentation. Firstly, all points are connected by a Delaunay-Triangulation using TRIANGLE (Shewchuck 1996). The triangulation establishes the neighborhood relation between the points. Then the points are segmented in a region growing process: A triangle which is not yet classified is taken first. If at least one point is a terrain point the triangle is classified as terrain and added to the segment 0 (indicating the terrain). If all three points of the triangle are classified as off-terrain the triangle starts a new segment. Iteratively, the triangles next to the actual segment are tested. If all the points are off-terrain the triangle is added to the segment. Otherwise the triangle is added to segment 0. A segment is finished, when no further neighboring triangle is available. The whole process stops, when all triangles have been assigned to a segment.

All triangles of one segment are merged to create the boundary of the segment. The boundary represents the building ground plan. Unfortunately the boundary typically contains very many points and is jagged (see Figure 1, right). So in the next step the boundary has to be simplified.

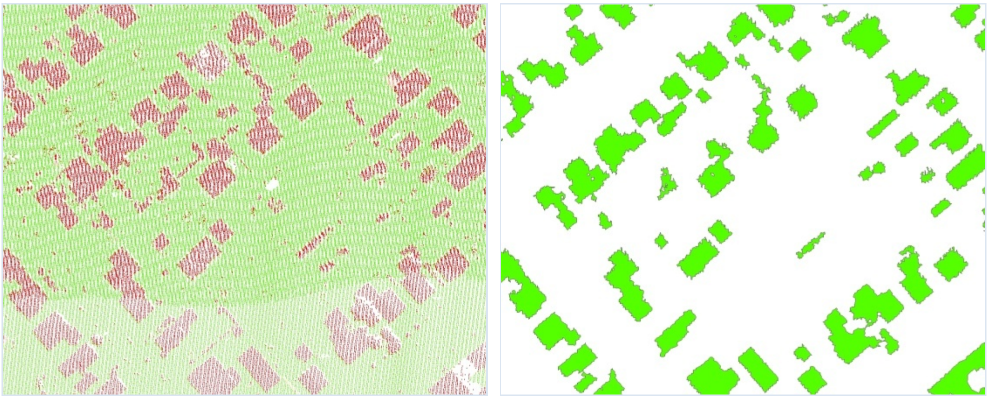

Figure 1: left: classification of laser points into terrain (green) and off-terrain (red) points; right: outlines of the off-terrain blobs.

SIMPLIFICATION OF SEGMENT BOUNDARIES

The problem is, that the well known methods for building generalization are designed for cartographic generalization purposes: they start from with a valid building ground plan and the goal is to transform it into a representation in a smaller scale. So they start with a real building ground plan at a given resolution described with a non redundant point sampling. This is not the case in our problem: here, the boundary is composed of too many points, the outline shape is irregular and is jagged; also, the general characteristics of the building shape are often not given. Furthermore, the representation not necessarily contains all the points considered as relevant for the building, e.g. important corner points may be missing.

This leads to difficulties when trying to apply the generalization algorithms. We verify this difficulty by trying to use approaches for reducing the high point redundancy (Douglas-Peucker-Algorithm – Douglas & Peucker, 1973), followed by an approach designed for cartographic generalization, which tries to retain building characteristics (CHANGE – Staufenbiel, 1973). The deficiencies of both approaches lead us to a new approach that tries to combine both characteristics (RANSAC plus Least Squares Adjustment).

Simplification using Douglas-Peucker-Algorithm

For line simplification the algorithm by Douglas and Peucker can be applied (Douglas & Peucker, 1973). The algorithm reduces the number of points of the original point set by recursively eliminating points that fall below the threshold of a potential remaining line. The threshold for the algorithm can be set according to the point density of the original laser points, as the position of the building boundary points can vary within this value. The results of applying Douglas-Peucker to the data are given in Figure 2. Segments that fall below the threshold of a desired building size (here 15m²) are shown in lighter color and are eliminated.

The line simplification with the Douglas-Peucker algorithm is good to reduce the number of points. But the results are not satisfying because the building characteristics are not necessarily retained. Furthermore, outliers in the data can be retained. Another drawback of the algorithm is that the simplified building can only be composed of a subset of the original points. If important corner points are missing in the original data, they cannot be recovered by the algorithm.

Building simplification with CHANGE

The program CHANGE of the Institute of Cartography and Geoinformatics is designed to simplify building ground plans. It uses a set of rules to eliminate too short elements of the outline. These rules eliminate protrusions and offsets, and also corners. The rules are designed for outlines that are non-redundant in the sense, that the minimal number of points is used to describe them. The result of applying CHANGE reveals that due to the high redundancy and the presence of noise in the data the building shape cannot be recovered satisfactorily (see Figure 2, right).

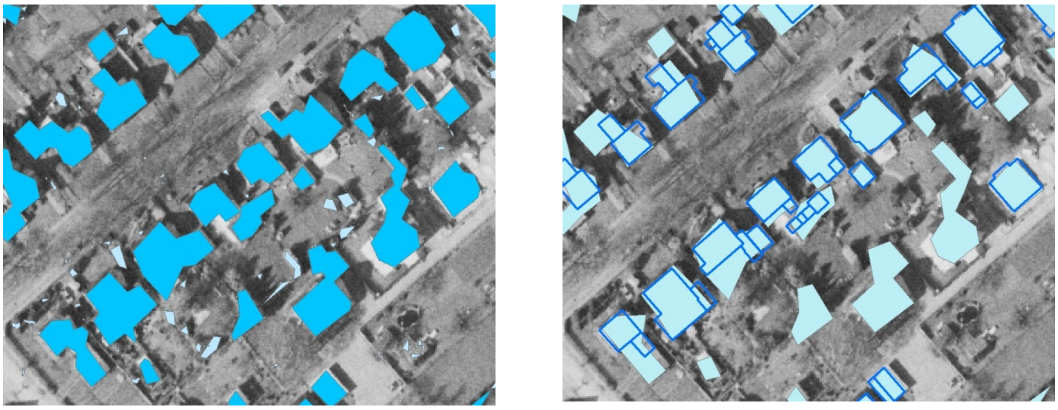

Figure 2: Situation after application of Douglas-Peucker-Algorithm (left) and after the application of CHANGE (right); for comparison the cadastral information is overlaid in dark blue outlines.

GENERALIZATION USING RANSAC AND LEAST SQUARES ADJUSTMENT

Obviously, neither Douglas-Peucker with its capacity to reduce redundant points, nor CHANGE with its property to simplify building outlines is able to adequately treat the given data. Therefore, we propose a method that tries to approximate the outline with a set of straight lines. This approach is motivated by the fact that buildings are man-made objects and mainly consist of straight lines that are linked using additional constraints concerning rectangularity and parallelism. We firstly extract straight lines with RANSAC, then these lines are adjusted to the original building outline using additional constraints that take the building characteristics into account, similar to Sester (2000).

Extraction of potential buildings facades with RANSAC

In a first step the building outline is described as a set of straight lines. To this end, the RANSAC algorithm (Random Sampling Consensus, Fischler & Bolles, 1981) is applied. RANSAC is a method that is able to find a model in a data set in a high presence of noise. The algorithm operates as follows:

- Random selection of as many data points as are necessary to determine the model
- Determine the model using the selected data points
- Calculate the subset of data points that have a distance to the model which is smaller than a given threshold *d* (this subset is called "consensus set"). All points with a distance larger than the threshold are considered as outliers. If enough points are in the subset, that subset is stored.
- Iteration of steps 1 to 3 *N* times

After *N* iterations that subset which contains the most points is chosen.

In our case, the task is to determine *m* straight line segments of subsequent points in the given boundary. Thus, the model is a straight line, which needs two points to be uniquely determined. The threshold for the distance has to be selected according to the noise of the boundary. In our case it is a value between 0.5 and 1 m. The number of straight lines *m* depends on the complexity of the ground plan. The minimum number is 4 (which determines a simple rectangular building).

The algorithm therefore starts with the assumption, that a straight line representing a building façade has to consist of l=r/4 points, with r being the number of points of the outline. Randomly, two points are selected from the point set, which form a straight line. Then, all neighboring points are incrementally collected which fit to that line (i.e. which have a distance value smaller than the threshold). Note that only neighboring points are incrementally added, as the assumption is that the straight line has to be formed of consecutive points. If at least *l* points are found that fit to a straight line, it is stored and the points belonging to the line are eliminated from the boundary. The whole process is iterated with the remaining points. Due to the elimination of points, the local neighborhood of the remaining points changes and has to be adapted.

If not enough consensus points are found, the random selection is repeated. After a certain number of iterations where no appropriate line could be found, the required number of points *l* is decremented. This is done in order to account for a possibly wrong assumption concerning the number of segments of the building outline. After a candidate line is found, an adjusted line can be calculated using all the candidate points of that line in a regression analysis. This leads to a better approximation of the line.

In the Figure 3 some results for the detection of straight lines are shown: on the left hand side the original building is shown, in the middle, the straight lines generated by the randomly chosen start and endpoints of a line are shown, whereas on the right side the adjusted lines are given. It is clearly visible that the adjusted lines fit much better to the original points and thus better represent the outline of the buildings.

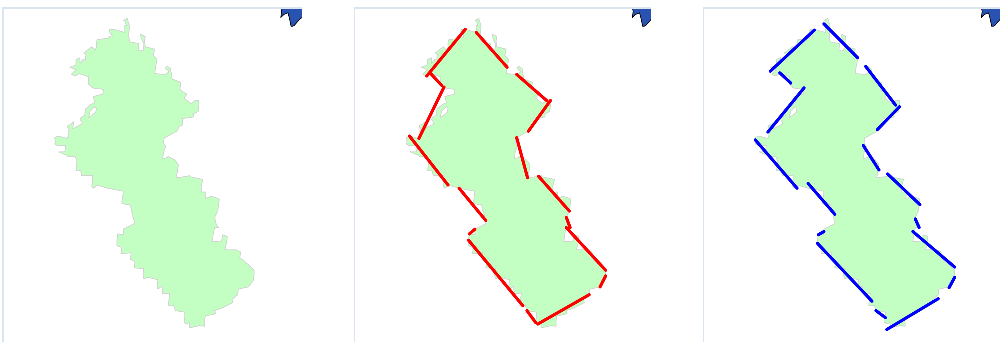

Figure 3: Original building outline (left); straight lines (middle); straight lines after regression analysis (right)

Figure 4 shows the result of the segmentation using different thresholds for the distance of the points from the line. It is clearly visible that larger thresholds lead to longer and more generalized segments, but also to a tentative omission of some segments, whereas smaller thresholds create an oversegmentation with small lines that also follow the jagged boundary and contain outliers. In the example, a threshold of 0.7 seems to be a good compromise between oversegmentation and overgeneralization.

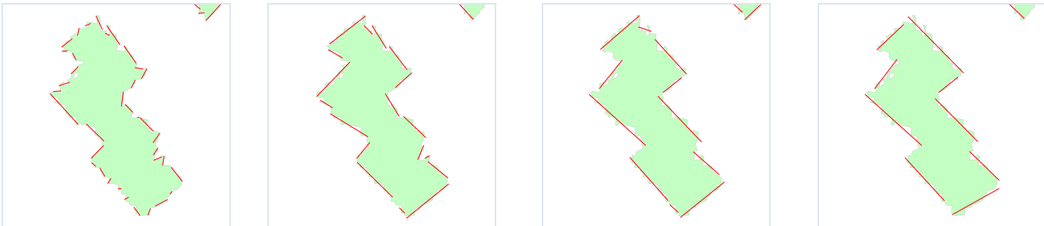

Figure 4: Different distance thresholds: 0.5m, 0.7m, 1.0m, 1.2m lead to different generalization levels

Combination and Adjustment of Straight Lines

In a next step, these straight line segments have to be combined to form a meaningful building outline. Meaningful means that typical buildings consist of mainly parallel and rectangular facades. The task is therefore, to connect adjacent straight line segments using parallelism and rectangularity as constraint. This can be formulated in terms of a Least Squares Optimization process. In Least Squares Adjustment the unknown information is determined by a set of observations. A function is set up that describes the observations in terms of unknowns, leading to the so-called functional model. The stochastic model describes the accuracy of the observations. The Least Squares Adjustment finds the optimal solution by minimizing the corrections of the observations.

The unknowns in our case are the parameters of the straight lines that set up the generalized building outline. The lines are given in parametrized form with parameters A, B, C.

There are three types of observations that are introduced in the process; they have to be formulated in terms of functions of the unknowns:

1) The straight lines are described as additional parameters in parameterized form:
$$A_i x + B_i y + C_i = 0$$
With the normalizing constraint:
$$A_i A_i + B_i B_i = 1$$

2) The points of the original outline:
Each point P(x,y) is introduced in the line equation of the corresponding line *i* leading to one observation equation.
$$A_i x + B_i y + C_i = d$$
In the ideal case, the points are lying on the straight line thus to the required distance observation *d* = 0; The accuracy of the points (stochastic model) is set according to the accuracy of the determination of the boundary points.

3) The angles between adjacent straight lines:

The angle *alpha* between two lines can be determined by vector product or by cross product of the normals of adjacent lines *i* and *j,* respectively:

$$A_i A_j + B_i B_j = \cos(\alpha)$$

$$A_i B_j - A_j B_i = \sin(\alpha)$$

Both equations are used in order to stabilize the system especially in the vicinity of right angles or parallelism (alpha = 90 degrees or 0 and 180 degrees, respectively).

The observations 1) are set up for all the straight lines generated in the preprocessing step with RANSAC. For each line, approximate values for the unknown parameters A,B,C are determined using the RANSAC lines. For each point of a line the observation equation 2) is set up. For all consecutive lines, the angle observations 3) are set up. Depending on the value of the angle, the target angle value is either set to be rectangular or parallel. This decision takes the deviation of the angle to 90 degrees or 180 degrees into account. In our case we used the threshold of 20 degrees: if the difference of the angle to rectangularity or parallelism is below 20 degrees, then this angle is fixed to be rectangular or parallel. Fixing is achieved by using a very high weight for this observation.

Angle values outside this range will be kept, however given a lower weight in order to allow for an adaptation in the iterative adjustment process. In later iterations (here starting in iteration step 4), the assumption is that the previous fixing of the unambiguous angles already lead to a certain rectification of the neighboring angles. Then, the angles are tentatively set to the closer direction – either parallel or rectangular – however, with a lower weight than the fixed angles. This then can also lead to a later rectification of these lines, but does not enforce it when the shape of the outline speaks against it.

In this way, rectangularity and parallelism of buildings will be favored, however, deviations from this will also be tolerated, thus allowing also the reconstruction of non-rectangular shaped buildings (see Figure 6).

Figure 5 shows the result of different steps of the algorithm.

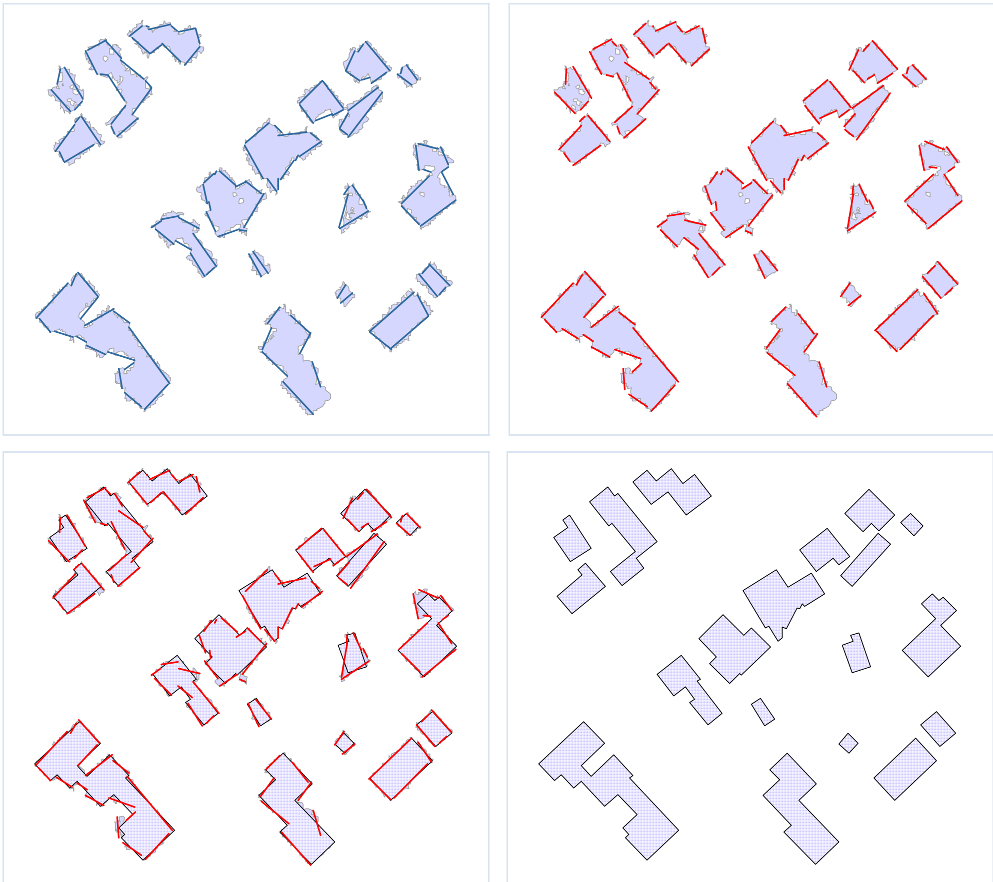

Figure 5: Example for the processing of a larger extent of the area: original buildings with extracted lines (upper left) and adjusted lines (upper right); adjusted objects with adjusted lines overlaid (lower left), adjusted objects (lower right).

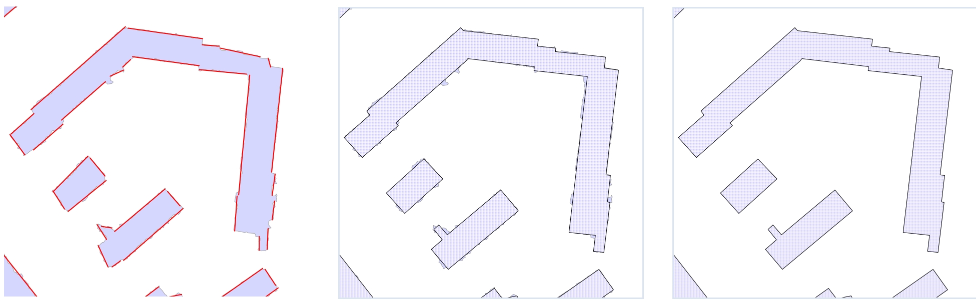

Figure 6: Example for a non rectangular object, which is nicely reconstructed: left: extracted and adjusted straight lines; middle: adapted ground plan overlaid over original situation: right result.

Due to the random generation of straight lines, there is a certain non-determinism in the whole procedure. This is visualized with the following example in Figure 7. Observed that in the first case the upper right building is reconstructed as square, as only four straight lines have been extracted. In the second case, the building is reconstructed as L-shaped building, as two corresponding straight lines have been extracted on that building side.

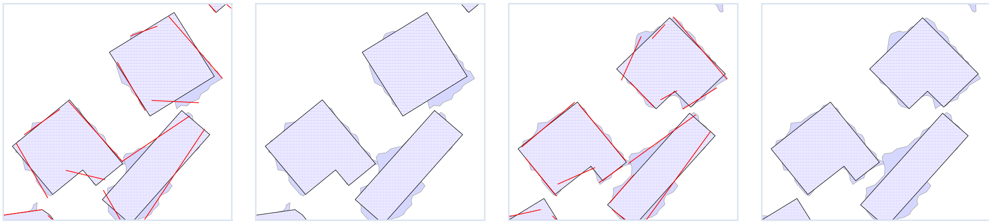

Figure 7: Two runs of the algorithm lead to slightly different results: a) extracted straight lines, b) reconstructed buildings; c) second run, extracted straight lines, d) reconstructed building.

Figure 8 shows a larger area of the processed data. The comparison with the original data shows that the detected "blobs" are nicely approximated using the constraints of the algorithm. The building forms correspond to typical building shapes. In the example, a threshold of 1m has been chosen for the straight line extraction with RANSAC. This leads to the fact, that small details of the building shapes are not recovered, but generalized. The overlay with cadastral information shows on the one hand a good overlap and correspondence of existing buildings. What is also nicely visible are new buildings, and also buildings that have been extended, i.e. the changes.

As the regions have been delineated using all off-terrain points, it is however possible, that some of the areas (or parts thereof) represent other non-building objects like trees. Therefore, new buildings or extensions of buildings should further be checked whether they could potentially also represent a tree. Our current work is focusing on the analysis of the 2.5D-shapes of the off-terrain surfaces. In case of buildings, they form roofs that are typically represented by planes; in case of trees, there is no such regular surface, and neighboring triangles point into different normal directions. In this way, vegetation can be identified and deleted before the shape approximation is done.

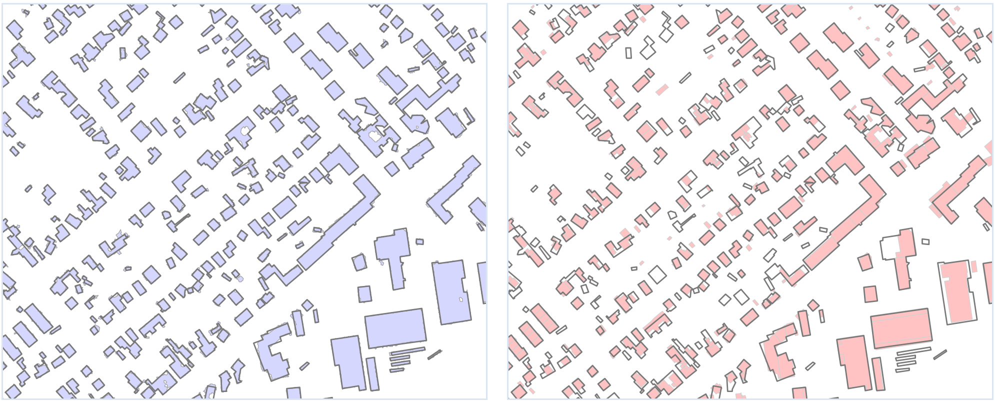

Figure 8: Result of a larger area: original data (upper left); automatically generated ground plans (upper right); result overlaid over original data (lower left) and over cadastral information (shaded polygons) (lower right).

SUMMARY AND OUTLOOK ON FURTHER WORK

In this paper we presented our research on the reconstruction of building ground plans from laser scanning data. In a first step, off-terrain laser points are classified from the raw point cloud and grouped to form potential building blobs. Then, a building shape is reconstructed from this jagged blob. We presented several approaches, of which a robust RANSAC algorithm is able to compensate for the high degree of outliers. As shown in the examples, the approach is able to find an optimal shape given the original data points in terms of the outline generated by the laser data and additional constraints which characterize a building.

The approach of combining RANSAC with Least Squares Adjustment is able to compensate and tolerate the high degree of noise that is in the data. It is powerful in the sense, that it prefers rectangular buildings, but does not enforce it, if the underlying data does not support it. The approach has similarities with the method proposed by Shan & Sampath (2007). The main advantage of our method is its possibility to also generalize non-rectangular buildings. Also, the main directions do not have to be determined.

The RANSAC approach, however, as indicated by the name, also includes some degree of randomness in the process. Although long and best fitting lines are found first, there are always several possibilities for selecting straight lines. The final adjustment does depend on these initial values – although there is some compensation possible by the constraints introduced. Another issue that has to be taken care of in the near future is the fact that the local decision to the nearest angle (either 90 degrees or 180 degrees) can lead to global inconsistencies. To prevent this, several options can be undertaken, which however, must be investigated in detail, e.g. fixing only n-1 of the possible n angles or trying to determine the value of the missing angle. Here, mathematical approaches like proposed by Brenner (2005) can be applied to determine the number of necessary conditions.

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