VECTORIZATION, EDGE PRESERVING SMOOTHING AND DIMENSIONING OF PROFILES IN LASER SCANNER POINT CLOUDS

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ABSTRACT:

The 3D geometry of an object can be captured very efficiently using a terrestrial laser scanner. By modelling and visualisation of these 3D data, it is possible to obtain vectorized geometric information of the object. Many users prefer to work on profiles, motivated by the handling of paper prints in the field by their own familiarization. Profiles extracted from laser scanner point clouds will inherit the noise characteristics of the original points. The effect of noise can be reduced by applying filtering operations. Straight profile sections can be smoothed by using a straight line filter kernel, while incurved profiles can be smoothed by arc-shaped structure elements. Because of the scanner resolution and the beam divergence, edges are usually not measured exactly. The paper presents an edge preserving algorithm to extract and smooth profiles and an approach for automatic vectorization. Smoothed laser scanner data profiles are represented as key points, straight line and arc segments. In addition to the profile vectorization, a CAD-format oriented dimensioning is derived from the data and added to the output. Results from practical applications in cultural heritage documentation and as-built documentation are shown. A profile length comparison between automatically extracted profiles and manually vectorized lines shows a standard deviation σ of 7 mm and a maximum deviation of 1.2 cm.

1. INTRODUCTION

Terrestrial laser scanners capture three-dimensional geometry data of an object in a short period of time and save this information in 3D point clouds. These dense 3D point clouds offer many possibilities concerning the further use of that data: Interactive measurements, profile extraction, 3D modelling or automations in respect of object detection. Many users, especially in the field of cultural heritage and archaeology, prefer to work on profiles (for instance horizontal or vertical cuts in regular intervals) to facilitate the interpretation, driven by the handling of paper prints in the field and their own familiarization. Profiles extracted from laser scanner point clouds are characterized by noise. The size of the noise mainly depends on the utilized range finder technique (phase shift or time of flight measurements) of the laser scanners (Böhler & Marbs, 2004). Applying filtering operations the noise can be reduced. Edges measured with a tachymeter in building recording applications get a smoothing effect caused by the beam divergence (Kern, 2003). The same effect is given in laser scanner point clouds, aggravated by the random point distribution and the scan resolution of a laser scanner. That means, it is unlikely that a laser scanner point hits an edge. Becker (2004) extracted edges in laser scanner point clouds by the intersection of surfaces. An edge position in a 2D profile without a smoothing effect can be obtained by the intersection of two straight lines. To take advantage of this, an algorithm for edge preserving smoothing was developed, wherein the edge positions are calculated by the intersection of straight line elements fitted into the data. Treating these edge positions as key points, a CAD-oriented vectorization of the profile data consisting of linear and arc-shaped elements can be obtained. Moreover, CAD-like dimensioning information can be generated automatically during the edge extraction process.

This paper deals with an edge preserving algorithm to smooth profiles (section 2.2). A structure element and a rotating line are used to separate points in the neighbourhood to guarantee a correct smoothing. Curved profiles are smoothed by arc fitting. An optimisation of the smoothing is reached by adapting steering parameters (section 2.2.2). Profile describing points, like edge key point (section 2.4) and end points (section 2.5) will be calculated. By using these kind of points a vectorization will done. In addition to the profile vectorization, a CAD-format oriented dimensioning is derived from the data and added to the output (section 2.6). Results from practical applications in cultural heritage documentation and as-built documentation are shown in section 3. Finally a conclusion with a discussion completes this article.

2. METHODS

2.1 Profile extraction and smoothing

In detail, the extraction and smoothing procedure works as described in the following. Profiles of a laser scanner point cloud are produced by defining an 'origin-plane'. This could be an equidistant plane for the XY-, YZ- or XZ-plane or an arbitrary plane described by three points. All points inside a layer with a defined thickness along the plane are separated from the point cloud.

Each laser scanner point is smoothed by calculating a new and individually adjusted straight line through its neighbouring points. The point to be smoothed defines the centre of a pre-defined square structure element. All points inside the structure element are the input data for the straight line fitting (Figure 1, left structure element). The mathematic model for the straight line fitting is shown in 2.2.1. Irregular curved profiles can be smoothed by fitting an arc element. If the residual of the point obtained by smoothing is less than a pre-set smoothing tolerance, the point will be smoothed, alternatively not. Then the structure element proceeds to the next point. Processing edges in a profile with the standard smoothing (Figure 1, right structure element) will result in rounded edges. This can be overcome by an edge preserving profile smoothing technique as described below.

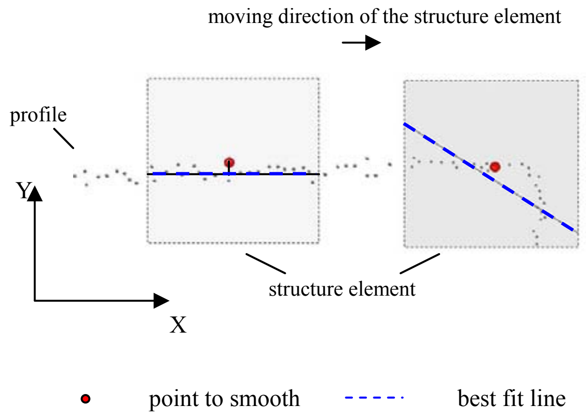


Figure 1. Smoothing procedure with moving structure element

2.2 Edge preserving smoothing

To realize edge preserving smoothing, the filtering inside the structure element is performed with a rotating straight line element. This line is placed through the point, which is to be smoothed, and rotates successively in constant angular intervals depending of the structure element size. For each line position, the orthogonal distance of all points is determined, and all points with a distance to the line smaller than a pre-set line tolerance are counted. The position with the highest score defines the approximate position of the fitted line, and only the counted points are used as input data for the line fitting algorithm (Figure 2). This procedure performs well in preserving edges during the smoothing procedure, if the size of the structure element and the line tolerance settings are adapted to the resolution and the accuracy of the point cloud data. Each smoothed point is saved in a list with its residual, the improved coordinates and its fitted line parameters (centre point, direction vector).

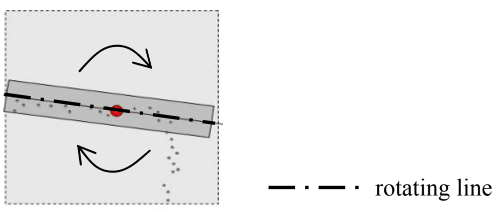


Figure 2. Rotating line placed at the current point to smooth

2.2.1 Straight line adjustment:

To smoothen the profiles, a line of best-fit is calculated. A best-fit line is defined as the line with the minimum sum of squared distances of all valid points inside the structure element. The parametric form of a straight line is given in (Eq. 1). To find the best-fit line, the centre point P_0 (X_{P0}, Y_{P0}) of all input points and the direction of that line have to be determined. The direction vector ***d*** is obtained by solving the eigenvalues of matrix ***B*** (Eq. 3), which is built with the coefficient matrix ***A*** (Eq. 2) (Luhmann et al., 2006). Finally, the corresponding eigenvector of the maximum eigenvalue is equivalent to the direction vector of the best fit.

$$\begin{bmatrix} X \\ Y \end{bmatrix} = \begin{bmatrix} X_{P0} \\ Y_{P0} \end{bmatrix} + t \begin{bmatrix} \mathbf{d}_X \\ \mathbf{d}_Y \end{bmatrix} \quad (1)$$

$$\mathbf{A} = \begin{bmatrix} X_i - X_{P0} & Y_i - Y_{P0} \\ \dots & \dots \\ X_n - X_{P0} & Y_n - Y_{P0} \end{bmatrix} \quad (2)$$

$$\mathbf{B} = \mathbf{A}^T \mathbf{A} \quad (3)$$

where X, Y = coordinates of a point on the line
X_{P0}, Y_{P0} = coordinates of the centre point
X_i, Y_i = coordinates of all points inside the structure element
n = number of points inside the structure element
d_X, d_Y = components of the direction vector
t = straight line parameter

In case of vertical (slope: 90°) and horizontal lines (slope: 0°) the determinant of ***B*** is 0. This indication is used to determine the correct direction vector. Both cases (horizontal and vertical) are checked. For each case the sum of distances *d* of all points to the line is built (Figure 3). The case with the lowest sum is the right direction.

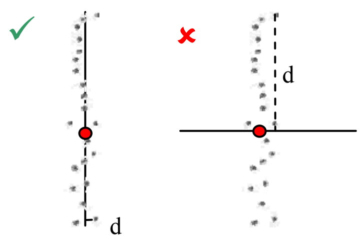


Figure 3. Case checking to identify the direction (det(***B***)=0)

2.2.2 Steering parameters:

An optimisation of the smoothing is reached by adapting the steering parameters of the smoothing algorithm, like smoothing radius *p*, smoothing tolerance T_S, line tolerance T_L of the rotating line and iterations *i* of the smoothing procedure.

Smoothing radius

The number of points which influence the smoothing procedure is given by the smoothing radius *p* (Figure 4). This value is equal to the structure element size. A bigger smoothing radius increases the number of points in the neighbourhood. For standard value the smoothing radius should have more than the twenty fold size of the average profile point distance.

Smoothing tolerance

The smoothing range depends on the smoothing tolerance T_S. This may be a pre-defined fixed value (adapted to the point accuracy of the range finder) or a variable smoothing tolerance derived from the standard deviation of the residual of all points of the fitted line. In our data taken with a laser scanner with a range precision in the order of 8 mm, a variable smoothing tolerance was chosen.

Line tolerance of the rotating line

In case of a profile edge inside the structure element, the line tolerance T_L extracts the points to be used for line fitting. It is useful to define the line tolerance as a function of the average range noise of the point cloud. A typical standard value would be two times the range noise.

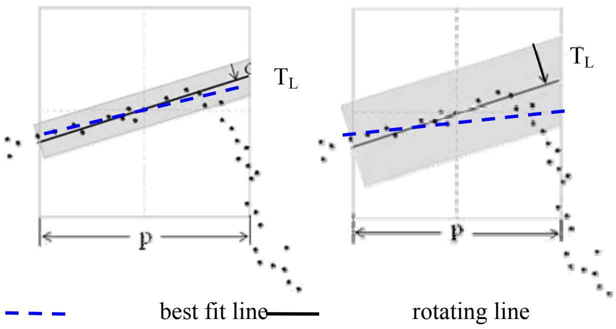


Figure 4. Influencing of the best-fitted line by an increased line tolerance value T_L

Iterations

The smoothing procedure is an iterative process. In the first iteration *i*, the whole profile point list is processed and a new list with smoothed points is built. The following iterations work on the smoothed point list of the preceding iteration step. So the point list will be reduced in each step. The smoothing procedure stops either after a fixed iteration number or if a stop criterium determined during the process is fulfilled. By counting all points whose residual is less than the pre-defined minimum smoothing threshold, a percentage value is calculated. When the pre-defined percentage value is reached, the smoothing procedure will stop.

2.3 Combination of curved and straight line smoothing

Some buildings show a combination of curved and straight elements on their facade. Therefore a combination of a smoothing algorithm for curves and lines is required. When smoothing curved profile sections with straight line structure elements, the points will displaced towards the centre. So the outer hull of a curved profile would always be too small. Avoiding this, separate arc and line fitting is performed. As a first simple approach, the suitable element for each segment is chosen using the smaller error of unit weight of the adjustment as a decision criterium. In Figure 5, a smoothed profile of a mixed cross section is shown. The arrows mark the area of the arc-smoothed points. All other points are smoothed by straight line elements.

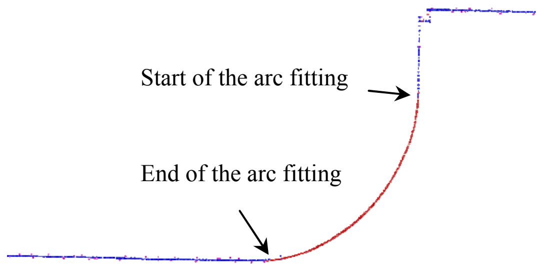


Figure 5. Smoothed profile by using a combined arc and line fitting

2.4 Edge key point determination

The procedure as described in section 2.2-2.3 will perform a smoothing of the profile data without causing rounding effects at edges in the profile. However, the smoothed profiles will still suffer from the sub-sampling characteristics of the laser scanner data, which will also truncate edges. This can be overcome by using the information of the adjusted lines of the points close to an edge in the profile. When a significant variation in the straight line slope parameter *m* (Eq. 4) indicates an edge, a new key point representing the edge can be obtained by intersection lines from both sides of an edge point as described below.

After the smoothing procedure, the calculation of the edge points, which is obtained from the slope of each point inside the structure element (each point has another slope, because of the moving direction of the structure element) is performed. On each point a structure element is placed. The slope of this point is compared with the slopes of all other points inside the structure element. If a significant change of the slope is recognized, the intersection of the fitted lines is determined. If the intersection angle is greater than a pre-defined edge angle, the intersection will be saved. For each point close to the edge this edge point is calculated. Thus, this edge point was calculated several times which provides the option to determine quality parameters as the standard deviation. This value can be regarded as the mean variation of the edge placement.

$$m = \frac{1}{2}\arctan\left(\frac{2\sum_{i=0}^{n}(X_i - X_{P0})(Y_i - Y_{P0})}{\sum_{i=0}^{n}(Y_i - Y_{P0})^2 - (X_i - X_{P0})^2}\right) \qquad (4)$$

2.5 End point determination

Because of self-occlusions or occlusions caused by objects (people, cars, vegetation), scan shadows may be present in the data. Profiles including scan shadows are characterized by discontinuous point sequences. The end points of such a profile have to be found (Figure 7a. green points). An end point is defined as the last point of a point sequence with a distance less than a pre-defined threshold to his neighbour point. During the smoothing process, a pre-filtering in respect of the end points was done. While fitting a straight line, the line parameter *t* is sorted by the size. Thereby the point to be smoothed has the straight line parameter *t*=0. If there are only negative or only positive line parameters the point could be an end point. These points are marked with a flag (Figure 6, yellow point) and will used later in a second filtering. Due to points which were not smoothed and so not included in the last iteration, caused by a residual greater than the smoothing tolerance T_S, the marked points from the pre-filtering are controlled in a second filtering relating to the unsmoothed points. The embedded angle α between the farthest neighbouring point (Figure 6, green line) and all other points inside a structure element and the proposed end point is calculated. If angles are recognized greater than 90 degree the centre point is no end point, otherwise it is an end point.

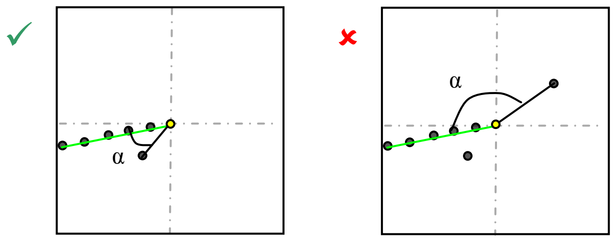


Figure 6. End point determination (left: α<90°; right α>90°)

2.6 Vectorization and dimensioning

Finally the smoothed profiles are automatically vectorized and dimensioned. Starting from the types of points (profile sequence end and edge points) and the knowledge that two lines are combined in one point, the automatic vectorization is performed. Therein a straight line, placed at the first sequence end point (start point), rotates. The algorithm finds the line with the most points on or close to the line (buffer in this case: 3 mm) (Figure 7a). With all points between the start point and the point with the greatest line parameter, an adjusted straight line (dotted line in Figure 7b) is determined. The intersection point of the normal distance from the last point and the adjusted straight line defines the break point (Figure 7b). The break point is set as new start point and the routine starts again (Figure 7c).

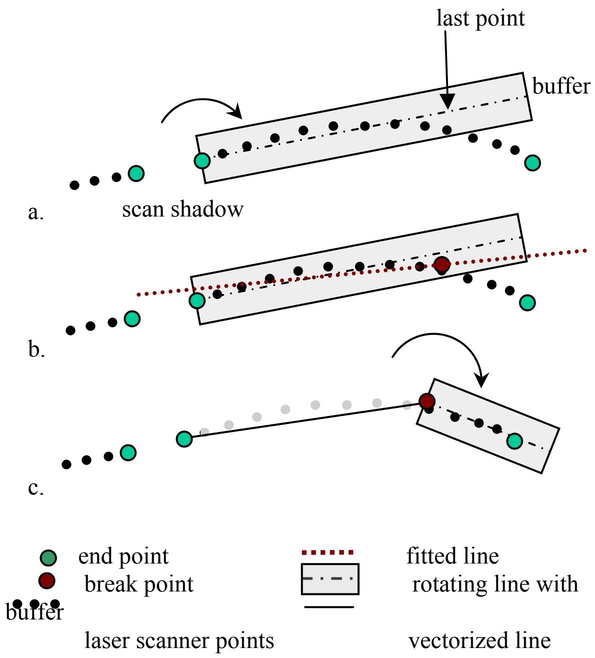


Figure 7. Steps of the vectorization (schematic visualisation)

Edge and end points are also considered. If such a point is recognized inside the buffer, the point is automatically set as break point. Is it an edge point, the algorithm continues with the edge point as starting point. An end point stops the vectorization of that line, and the whole procedure starts with a new end point from the list. All points inside the buffer are deleted from the point list, as well as the used end and edge points. If an end or edge point was used, its score is increased. They are deleted if the score indicates 1 for end and 2 for edge points. The vectorization routine stops if all end points are used. If a closed room or a building was scanned without occlusions, the profile is free of interruptions and also free of end points. In this case the procedure works only with edge points. Basically, the procedure could also be limited to a vectorization purely on the basis of edge and end points. Keeping some profile points in the data by the procedure as described above leads to a controlled thinning of the points during the vectorization especially in the case of irregular profiles, which occur quite frequently in cultural heritage and archaeology applications. This gives the option of a controlled generalization during the vectorization.

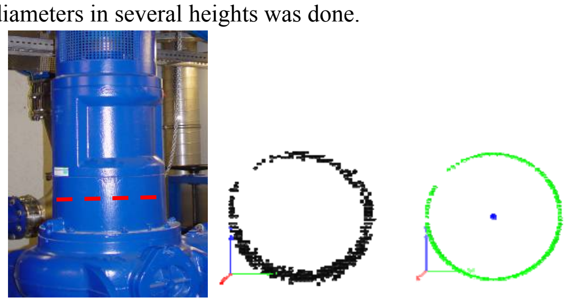
The dimensioning is done by summing up all saved lengths between the end and edge points and by placing the resulting numbers at a proper position in the VRML output (Figure 10). Also a marking of distinctive points, like edge points, with the point number or coordinates is possible.

3. RESULTS

The practical data, which were used to verify the techniques described in section 2, were acquired with a terrestrial laser scanner Riegl LMS-Z420i. This panoramic view scanner has a measurement range up to 1000 m and a point accuracy of 8 mm (Mulsow et al., 2004). The output format of our C++ routines for profile extraction is a VRML file (*.wrl) for the smoothed points and a VRML and also an AutoCAD file (*.dxf) with the vectorization and dimensioning.

3.1 Curved Profiles

One data set was scanned in a waterworks pumping station. The circular cross-section of a pump was smoothed by fitting an arc element. Figure 8a shows a pump with its cross section scanner data (Figure 8b). The smoothed profile with the centre point and three unsmoothed points (outliers) is shown in Figure 8c. By increasing the structure element in a way, that all points are used for smoothing (360° arc element), each point has the same smoothing tolerance and all smoothed points are used to adjust a circle. A similar procedure was used in Maas et al. (2008) to locate tree stems in horizontal cross sections of 3D point clouds. Applying the same procedure the determination of stem diameters in several heights was done.



a. b. c.

Figure 8. a.) pump, b.) noisy cross section, c.) smoothed points

The variable smoothing tolerance T_S = 1.66 cm was determined by the double standard deviation of the residuals of all points. The biggest recognized residual of one point resulted in 1.12 cm. Therefore all points have been smoothed applying the determined smoothing tolerance. A standard deviation of unit weight of the adjustment of σ_0 = 8.34 mm and standard deviations of X, Y and radius smaller than 1 mm (σ_X = 0.54 mm, σ_Y = 0.60 mm, σ_{radius} = 0.44 mm) were obtained. Besides the smoothing the radius and the position of the pump was determined.

3.2 Edge preserving smoothing

The famous Dresden Frauenkirche (Figure 9, left) was scanned from 14 different scanner positions and with a scan resolution of 0.05°. 2 m above ground a horizontal profile with a thickness of 12 cm was extracted (Figure 9, right). Some scan shadows, which are caused by lanterns and moving people, are minimized by overlapping scan areas. The profile covers an area of 41 m x 41 m, 34 000 laser scanner points and more than 200 edge points.

Figure 9. Dresden Frauenkirche (left), horizontal profile (right)

The profile was automatically smoothed, vectorized and dimensioned. A detailed view is shown in Figure 10. Using the same unsmoothed profile points, an operator did a vectorization within 70 minutes in AutoCAD. Comparing eight of more than 200 vectorized profile lengths (manual vs. automated), a standard deviation σ of 7 mm and a geometric mean of 0.8 mm was obtained (Table 1). Table 2 shows the variations of the edge key points obtained by intersections.

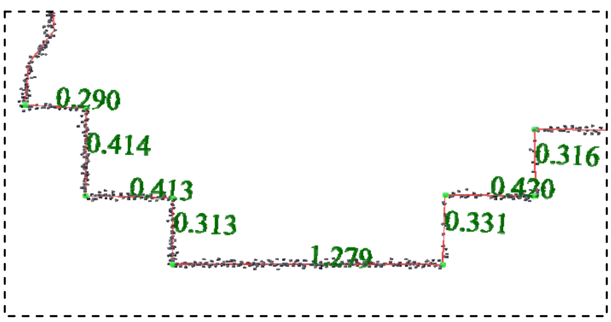


Figure 10. Vectorization and dimensioning (VRML output file)

Edge	Manual [m]	Automated [m]	Difference [cm]
1 → 2	0.296	0.290	-0.6
2 → 3	0.416	0.414	-0.2
3 → 4	0.408	0.413	0.5
4 → 5	0.313	0.313	0
5 → 6	1.289	1.279	-1.0
6 → 7	0.319	0.331	1.2
7 → 8	0.429	0.420	-0.9
8 → 9	0.313	0.316	0.3
Geometric mean			0.0875
Min.			0
Max.			1.2
σ			± 0.7

Table 1. Comparison of the manually and automatically vectorized profile lengths of Figure 10 (anti-clockwise edge counting; starting top left)

Edge	X [mm]	Y [mm]
1	9.46	2.98
2	8.96	2.30
3	11.32	4.00
4	8.74	2.68
5	6.20	2.24
6	3.33	8.63
7	2.58	5.65
8	4.79	15.10
9	3.97	8.20
Geometric mean	6.59	5.75

Table 2. Mean variation of the edges of Figure 10 (anti-clockwise edge counting; starting top left)

3.3 Combined smoothing algorithm

The example shown in Figure 5 was extracted from a building facade with a small tower (Figure 11) and has a size of 8 m x 3 m. The profile was smoothed with a straight line or arc structure element size of 80 cm and a variable smoothing tolerance. In comparison to a smoothing purely by straight line fitting (with the same parameters), the points have an average distance of 1.2 cm. That means the profile, smoothed with fitted lines, is shifted 1.2 cm towards the tower centre point.

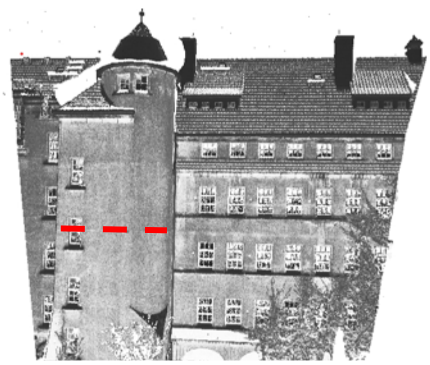


Figure 11. Point cloud of a curved facade (interrupted line = extracted profile of Figure 5)

Table 3 shows, for one point placed at the maximum curvature (in Figure 5), the accuracies and residuals of a straight line fitting and an arc fitting. The smoothing procedure at this point has a standard deviation of unit weight by fitting an arc of $\sigma_{0Arc} = 1.17$ cm and a standard deviation of unit weight by fitting a straight line of $\sigma_{0Line} = 4.50$ cm. By regarding the standard deviations of unit weights and the residuals (for this point and the biggest occurred residual), it is shown that an arc fitting suits best.

	Straight line fitting [cm]	Arc fitting [cm]
σ_0	4.50	1.17
Point residual	0.80	0.14
Biggest residual	7.30	3.41

Table 3. Comparison between a straight line and arc fitting of a curved profile

4. DISCUSSION & CONCLUSION

The presented profile extraction algorithm enables an edge preserving smoothing profile vectorization in 3D point clouds of building facades. Profiles are smoothed on the basis of fitting straight line or arc elements. Based on the filtering by these structure elements, outliers in front of a facade have no influence on the smoothing procedure. By defining a smoothing tolerance, the user can define the degree of generalisation. Edges in the data are preserved by a structure element rotation and score strategy. Rounding effects caused by the sub-sampling of laser scanners are compensated by inserting key points obtained from the intersection of straight line elements. The straight line and arc elements also allow for CAD-like output data formats, including dimensioning information.

Some more work remains to be done:

- Currently the computation time is still rather large, as for each straight line position the normal distance of all points has to be calculated. The use of a principle component analysis in the structure element to detect the approximate direction of a line or a RANSAC-like approach in the point selection may reduce the processing time significantly.
- Regarding the combination of straight line and arc fitting, the switch between line and arc elements still causes some problems. In many cases, some points within this section will not be smoothed. Furthermore, more complex profiles may produce non-satisfactory results.
- To determine the edge key point position, a minimum angle has to be set. This angle is used to define intersections points as edges if the intersection angle is greater than a pre-defined value. Obtaining good results this value should have the size of the minimum existing edge angle in profile. A too small angle may produce edge points at discontinuities in the profile, where no significant edges exist.

The CAD output format reduces the data possible and enables an interactive correction or an additional editing. The profile is represented with less points by saving only start and end point of each line. The accuracy assessment shows a maximum deviation of 1.2 cm between automatically generated profile data and a manual vectorization with the same unsmoothed profile points. This is sufficient for a representation of the automatically vectorized profiles in large scaled maps (1:25 or 1:50).

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