TERRESTRIAL LASER SCANNING IN ARCHITECTURAL HERITAGE – DEFORMATION ANALYSIS AND THE AUTOMATIC GENERATION OF 2D CROSS-SECTIONS

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ABSTRACT:

Thanks to its speed and accuracy, terrestrial laser scanning is gaining importance in the field of architectural and cultural heritage. Laser scanners are field-of-view devices that offer a dense point-wise sampling of an object’s geometry. The first part of this article addresses the question whether laser scanning produces sufficiently accurate results to be used for deformation monitoring of historical structures. A test setup using a masonry arch was prepared in which different scenarios were simulated. The structure was scanned at different times while moving one of its legs and the influence of different scan resolutions on the accuracy and the detectability of deformations were tested. Using a different setup, the influence on accuracy of different targets configurations, in particular orientations and distances to the scanner were tested.
In a second part, two prototype algorithms are presented for the automatic generation of cross sections based on point clouds. The first method is based on point splats. Point splats are an alternative for meshes for the surface-like reconstruction of point clouds. Their main advantages are the low computational cost and the ability to give an accurate representation of sharp edges and details. The cross sections obtained from our algorithm are compared to similar cross sections obtained from a mesh based surface representation. The second proposed method segments a sliced point cloud into outlier-free clusters based on techniques from robust statistics. The cluster is grown by fitting a parametric model and computing the residuals using a moving least squares approach. This procedure generates a piecewise smooth cross-section with sharp discontinuity representations. In order to prove the usability of the algorithm, the cross sections obtained from this algorithm are compared to similar cross sections obtained from a mesh based surface representation.

1. INTRODUCTION

Thanks to its speed and accuracy, terrestrial laser scanning is gaining more and more importance as a measuring tool in the field of architectural and cultural heritage. Terrestrial laser scanners allows capturing our built environment in a quick and easy way. They survey their subject by sending out a laser beam under varying vertical and horizontal angles and calculating the time interval between emitting a signal and receiving its reflection in order to determine the distance to the subject. The result of the measurement is a virtual three-dimensional point cloud representing the geometry of the scanned area.

This article focuses on two problems within the application of terrestrial laser scanning in cultural heritage documentation. Laser scanning in cultural heritage has mostly been used as a tool for as-built documentation and digital archiving. Although it captures enormous amount of points in an incredibly fast way, its accuracy comes short when talking about deformation monitoring. In the first part of this paper, the question whether the accuracy of current laser scanning techniques is sufficient for deformation monitoring of historical structures is addressed.

In a second part, we focus on the automation of point cloud processing. One of the deliverables often required when surveying heritage sites are as-is plans or cross-sections. We propose two methods for the automatic generation of these sections and discuss their potential for use in practice.

2. LASER SCANNING FOR DEFORMATION MONITORING

The main reason why laser scanning isn’t used for deformation monitoring a lot, is its relatively low single point accuracy. The precision that can be achieved with modern mid-range laser scanners varies from 5 to 25mm. This accuracy depends on the laser type and the measuring principle used, but it is also influenced by the measurement conditions such as the temperature, the wind, the surface roughness and last but not least the surface inclination angles. This is approximately 1 order lower in magnitude compared to traditional surveying techniques such as total stations or contact sensors.
However, the main benefit of laser scanners for deformation monitoring is the fact that no prior knowledge is required concerning critical zones. Whereas traditional surveying techniques generally perform single point measurements, laser

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scanners scan the whole surface. Although the single point precision of a laser scanner is not so good, the accuracy of a laser scanner can be upgraded by fitting surfaces to the collected points and as such average the errors on each single point. In order to optimize the accuracy even further, multiple scans of the same object can be acquired sequentially, increasing the number of points and thus theoretically improving the standard deviation of a single point measurement [Lichti, 2002].

In research literature several attempts to use the laser scanner for deformation monitoring can be found. Tsakiri [Tsakiri, 2006] publishes the results of a deformation measurement of a sea lock using a laser scanner which is fixed on a stable position. The point clouds are then segmented by fitting planes and the distances between these planes are computed as a deformation measurement. The detected deformation are in the order of 9 to 21 mm. Gonzales and Aguilera [Gonzales, 2008] use terrestrial laser scanning to perform 3 subsequent measurements of a dam in Spain. The first survey is done when the reservoir behind the dam is empty, and the second survey when it is filled. Between the second and the third survey, a tunnel was built close by. In order to orient the point clouds according to each other, they use artificial targets attached to an external reference system using total station measurements. The detected deformations between the first and the second measurement campaign fulfilled the expected pattern, resulting in deformation of 8mm in the center of the dam decreasing towards the edges. Between the second and the third measurement, deformations up to 18 mm were detected. Finally Gielsdorf [Gielsdorf, 2008] describes an algorithm that orients subsequent point clouds according to each other based on the automatic recognition of flat surfaces. His tests prove that deformations larger than 10 mm can be detected.

In this paper, the results of a test under laboratory conditions are presented which aimed at determining the sensitivity of laser scanning in order to detect deformations. The workflow for deformation monitoring using terrestrial laser scanning can be described as follows. A structure is scanned at two different times t_1 and t_2, assuming it deforms within this time frame. This results in two point clouds representing the structures' condition at these points in time. For the sake of simplicity we will assume that, at both instances, only one scan is made of the structure so that there is no need for registration of different point clouds. In order to be able to compare the two datasets from times t_1 and t_2, both point clouds must be positioned according to the same spatial reference system. This is a crucial step which we will call "orientation". However, laser scanners never measure exactly the same points two times in a row. Therefore at least one of the point clouds must be converted to a mesh. As such the distance from all points in one point cloud to its closest surface element in the meshed point cloud can be computed.

2.1 Test case

In order to study the minimum detectable deformation suing a terrestrial laser scanner, a test case was prepared. The object of the test measurements is a 90 cm high by 140 cm wide masonry arch (Figure 1). One of the legs of the arch was attached to a movable platform controlled by a screwing mechanism. The masonry arch was selected because of its rough but realistic texture, its high resistance to deformations and the high occurrence of arches in historical heritage buildings.

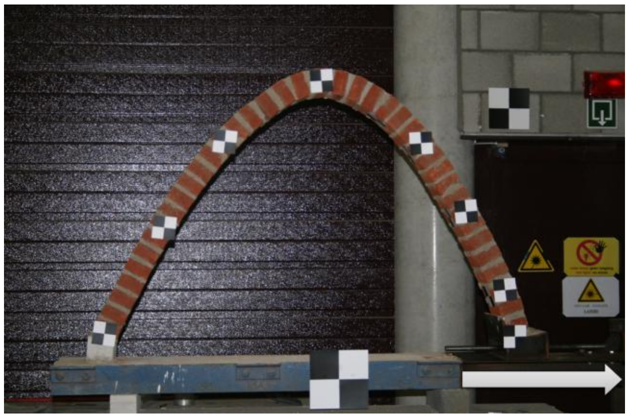

Figure 1. The masonry arch with paper targets

The scanner used in this test campaign was a Leica Scanstation 2 pulse-based scanner which has a per point accuracy of 4-6 mm. It was placed in a stable position and was not moved throughout the duration of the experiment. The arch was scanned multiple times, moving the right leg of the arch a few millimeters outwards between scans. The exact displacement of the foot was measured using an electronic vernier calliper with a precision of 0,1 mm. After each deformation step, two scans of the arch and its surroundings were made, one with a resolution of 5 mm and one with 1 mm. This allowed determining the effect of resolution on the accuracy of the results.

2.1.1 Experiment 1

Within the first experiment, the accuracy of the laser scanner is compared to that of a total station by comparing the measurements of an artificial paper target fixed to the movable platform. After each deformation step, the paper target was measured reflectorless using the total station and then scanned using the terrestrial laser scanner after which a target was fitted to the scanned point cloud.

In Table 1 the relative movements between two consecutive displacements are shown. By comparing the relative displacement any systematic errors are ruled out. Because the scanner and the total station are kept on their position, there is no uncertainty about the orientation between different point clouds. As both the total station and the laser scanner use the same measuring principle of reflectorless measuring, the errors are very similar.

	Total station		Laser scanner	
Relative Displacement [mm]	Measured [mm]	Error [mm]	Measured [mm]	Error [mm]
0,0	0,0	0,0	0,0	0,0
0,6	1,0	0,4	1,0	0,4
1,4	2,0	0,6	1,2	0,2
2,5	3,0	0,5	2,1	0,4
4,6	5,0	0,4	5,0	0,4
15,0	15,0	0,0	15,2	0,2
	mean error	0,3	mean error	0,3

Table 1. Accuracy of displacement measurements with total station and laser scanner.

2.1.2 Experiment 2

In a second experiment, the point clouds themselves were used to detect deformations. The point clouds measured after each deformation step were compared with a mesh of the original geometry of the arch. This brings up the first parameter influencing the measurements, namely the scan resolution. The higher the resolution, the better the local surface approximation. However, in practice, the proper balance between the required level of detail and the scan time needs to be determined. In this test case, scans were made with a resolution of 1 mm and 5 mm. The point clouds obtained were then meshed using the software Geomagic Studio, where the 1 mm resolution scans resulted in bad meshes because of oversampling. Oversampling occurs when the resolution is chosen so small that the distance between neighboring points becomes smaller than the error on the distance between scanner and object. For the Scanstation 2, this error on the distance measurement is approximately 4-5 mm.

Although the scans with 1 mm resolution and those with 5 mm resolution showed similar errors on the distance measurement when fitting targets in experiment 1, the oversampled mesh was not useable for comparison as there were too many holes. Oversampled point clouds lead to meshes with a very poor quality. This can be explained by the fact that the angle between neighboring elementary planes becomes too sharp, resulting in a very coarse surface. This can be seen in Figure 2.

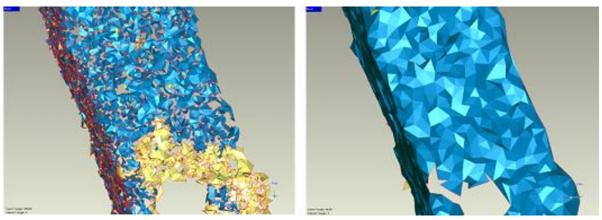

Figure 2. Meshed point clouds resulting from different point cloud resolutions, (left) 1mm, (right) 5mm

Tests were performed, applying smoothing algorithms or resampling the oversampled point clouds in order to reduce their point density. These resulted in negative effects on the accuracy of the data. For this reason it is very important that the resolution should be correctly chosen from the start. As a rule one should remember that the resolution must be at least as big as the error on the distance measurement from scanner to subject.

Further using only the 5 mm scans, the distances between the deformed point clouds and the original meshes were computed and plotted on a 3D model of the arch using Geomagic. A colored representation illustrates the computed distances between the models.

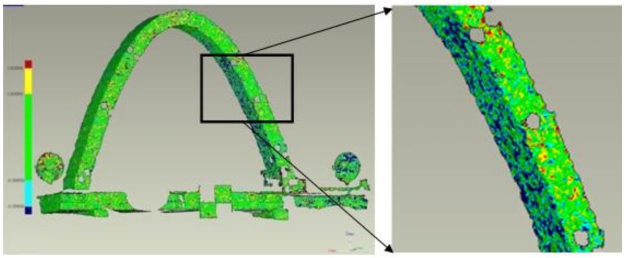

Figure 2. Deformation plot of a displacement of the right foot over 0,8 mm outwards. The blue color represents displacements to the right.

After fine tuning the color scale and sensitivity, it was possible to clearly detect deformations of the point cloud for a displacement of the foot of the arch over 0,8 mm. The distance plot for this step is shown in Figure 3. Bigger displacements led to (much) clearer results.

2.1.3 Experiment 3

In practice, it is very difficult to leave the scanner in a fixed position between two measurement campaigns. Nevertheless, it is crucial that the point clouds that need to be compared lie in the same reference system. In this experiment, four possible configurations (see Table 2) for the survey campaign are preset. Each of these configurations implies a different way of referencing the point clouds captured at t_1 and t_2.

Fixed scanner	+ Accurate + Little labor intensive - Expensive - Chance of theft or damage - Scanner position must be stable - Only 1 point cloud per scanner possible
Fixed targets	+ Accurate + Multiple point clouds possible - Requirement for stable target positions (Possible movement of targets)
Temporary targets	+ No permanent elements on the monument (No chance of damaging the structure) + No chance of moving targets - Complex survey of targets - Labor intensive
Stable surrounding elements in the point cloud	+ No permanent elements on the monument (No chance of damaging the structure) + No chance of moving targets - No absolute reference possible - Requires stable elements in the surroundings - Low accuracy

Table 2. Accuracy of displacement measurements with total station and laser scanner.

The first configuration was already tested in experiments 1 and 2. The other setups were tested as follows. For the second configuration a number of artificial targets (both black-and-white paper targets and reflective Leica HDS targets) were placed on fixed, stable positions around the arch. The third configuration was simulated by placing a larger amount of targets around the arch than necessary. In this way, targets could be deleted from the point clouds, resulting in point clouds, each containing a different set of targets. The coordinates of all the targets were measured by a total station standing on a permanent position during the whole experiment. Finally, the fourth configuration was simulated by deleting all the targets in the point clouds and using the surrounding walls and furniture as stable parts of the point clouds.

For the configuration using fixed targets, the average errors on the target measurements are almost identical to those of the configuration using a fixed scanner position (see Figure 4). The use of temporary targets led to a slightly larger error in the order of 1 mm. However, it has to be noted that the total station was not moved in our study. This means that in practice, a set error will be introduced by repositioning the total station. As this set error can be minimized by using a proper control network, it can be said that even temporary targets can be used for deformation monitoring.

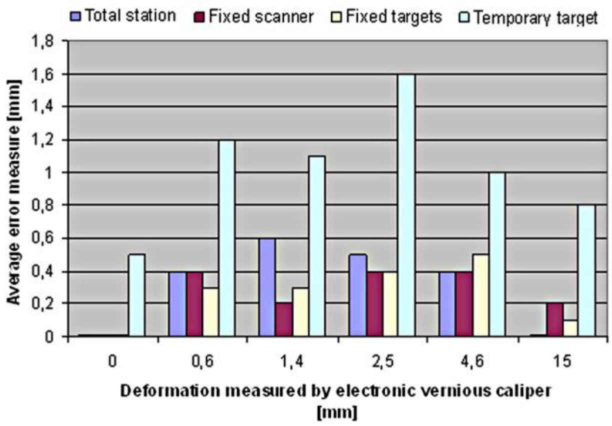

Figure 4. Average errors on the target measurements for different measurement configurations

The final configuration using stable elements in the environment lead to much larger errors in the order of 30 to 40 mm. It also has to be noted that in the presented test, the deformation subject was many times smaller than the stable area used for the orientation. In practice this will often be vice versa. As such this configuration cannot be used for deformation monitoring purposes.

3. AUTOMATIC GENERATION OF CROSS SECTIONS

Cross sections of measured point clouds can be used to obtain 'as-is' plans of historical buildings. This provides a very useful tool during restoration activities or for the mere documentation of architectural and cultural heritage.
Since point clouds are made up of individual points, cross sections cannot be obtained directly from the point cloud: the complex task of finding connecting points and determining where sharp features should be reconstructed is still an unsolved issue.
For these reasons, we propose two alternative solutions for the production of cross sections based on point clouds. A first attempt uses point splats as an alternative to a mesh, allowing a fast computation and an approximate surface reconstruction. A second, more complex method iteratively fits 2D primitives to a point cloud slice and tries to reconstruct a closed contour line using a moving least squares algorithm. Both methods are explained in the next paragraphs.

3.1 Cross-sections based on point splats

Point splats or laser splats, also called surfels (for *surface element*, Pfister et al., 2000) were first proposed as an alternative for meshes in computer graphics. Point splats are obtained by replacing each point of the point cloud by a small disk perpendicular to the local normal and with a radius large enough to cover the space until the next splat (Figure 5). Each of these disks forms a very local approximation of the real surface of the object. Point splats form a point-based representation of the object, meaning that they do not store explicit information on the neighborhood relationships between points (although they use neighboring points for the determination of the local normal and the splat size). Mainly for this reason, the computational cost for producing point splats is much lower than for a mesh.

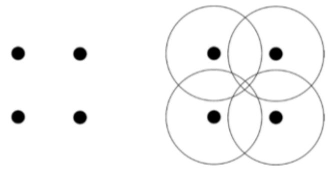

Figure5. Point splats (Böhm & Pateraki, 2005).

One of the advantages of point splats is that they extrapolate sharp edges and details in a very accurate way where the quality of the local surface approximation depends mainly on the algorithm used to compute the local normals.

3.1.1 Splat computation

Traditional normal computation based on principal component analysis smoothens the normals near discontinuities. In order to solve this issue, two filters were implemented that optimize the search for neighbouring points contributing to the correct local plane as described by Van Genechten [Van Genechten, 2009].
Firstly, a sphere with a specific radius, depending on the local scan density and the local surface inclination, is used to filter out points that are too far from the local surface. This mainly solves problems occurring near jump edges as shown in Figure 6.

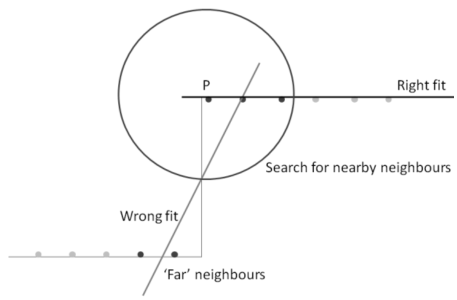

Figure 6. Correct and wrong fit on a jump edge (after Van Genechten, 2009).

A second filter rechecks the reliability of each normal based on its distance to the fitted plane. Points that lie further from the plane then a predefined threshold, which can be linked to the accuracy of the scanner, are reconsidered. These are mainly points near small details or near roof edges. For these points the normals are iteratively refined to better approximate sharp edges. In this way a very good approximation of the local surface normals is obtained, which will lead to accurate cross sections, as will be seen below.

3.1.2 Cross-section generation

After computing the local normals, the splat radius is calculated. This splat radius r depends on the local scan density which on itself depends on the distance of the point to the scanner.
After the splats are computed, a horizontal section plane is defined by selecting a point and a normal direction in the point cloud. Then, for every splat, the following steps are applied: first, the intersection line l between the section plane and the plane of the splat is determined. The orthogonal projection O' of the centre of the splat (O) on the line l is then computed and the distance |OO'| is tested (Figure 7): if this distance is bigger than the radius *r* of the splat, the splat has no intersection with the section plane. If |OO'| is smaller than *r*, the points A and B

are determined by adding and subtracting a vector parallel to l with length

$$v = \sqrt{r^2 - |OO'|^2} \tag{1}$$

from O’. Finally, the coordinates of A and B are converted from 3D to a 2D reference system in the section plane itself and stored in a vector.

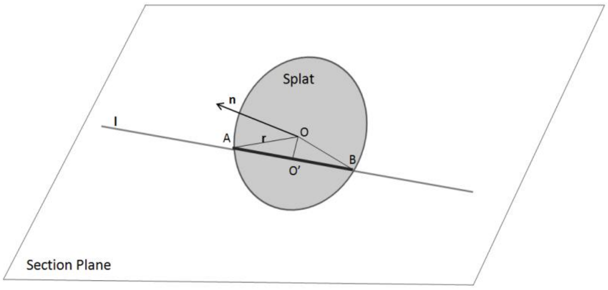

Figure 7. Intersection of a splat with the section plane.

It is clear that the cross sections resulting from the algorithm consist of a collection of small line sections AB. In fact, the line sections AB form a very local approximation of the real cross section, just as point splats form a very local approximation of the real surface. For this reason, the line sections AB can offer a good rendering of sharp edges and details in the cross section, while cross sections based on meshes smoothen out these details as shown in Figures 8 and 9. It is clear from these pictures that the splat-based approach leads to a much higher level of detail in the sections.

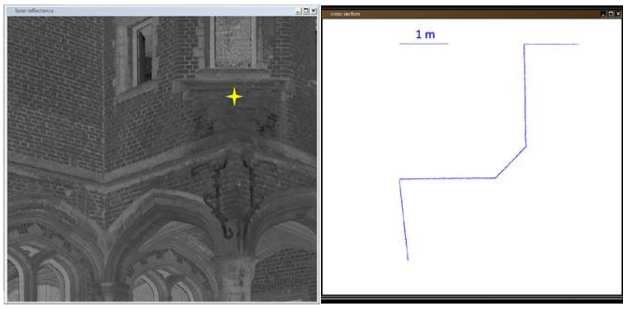

Figure 8. (left) Intensity image of a scan of the Castle of Arenberg (Heverlee, Belgium), (right) generated cross-section

It could be argued that sections consisting of scores of very small line sections instead of a smooth contour are un-aesthetic and unclear. However, when the sections are plotted on a 1/20 scale, which is used for fairly detailed architectural plans, the line sections melt together to form a nearly continuous contour. Additional smoothening is therefore not needed when using the sections as a simple visual working tool. One good reason to smoothen the sections out would be to reduce the amount of data, making it possible to import the section in CAD software. In (Demeyere & Herinckx, 2009), a method is proposed to do this without losing much detail and accuracy.

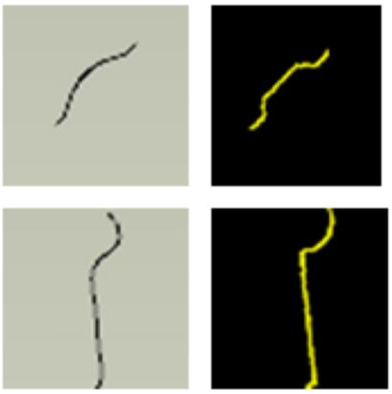

Figure 9. Comparison of details in a mesh-based (left) and a splat-based (right) cross section.

3.2 Cross-sections using moving least squares

The cross-sections obtained using the point splats are good for visualization, but are not useful for further processing. A second approach uses a moving least squares algorithm to grow and fit two-dimensional higher order primitives to a point cloud slice.

3.2.1 Forward searching using LMS

This algorithm uses the principles discussed by Fleishman [Fleishman, 2005], but in two dimensions only. It starts from a point in a local smooth area, which is determined on the basis of the local normal computation using a principal component analysis. It then iteratively adds new neighbouring points while constantly (re-)fitting a geometrical primitive (line or circular element) to the points using a Least Median of Squares optimization and analyzing the residuals of all the points. The points added are chosen based on their residual where points with smaller residuals are added first. This is called a ‘forward search paradigm’.

The power of the forward search algorithm can clearly be seen from the residual plot in Figure 10. It shows the residuals of all points along the Y axis and the iterations on the X axis. For every iteration, a new point is added and the primitive is refitted. The plot shows two groups of lines: the lines near the bottom that generally overlap and represent the residuals of the points that closely fit the primitive (inliers); and the other lines that basically represent larger residual values originating from points that are not part of the current growing segment (ouliers).

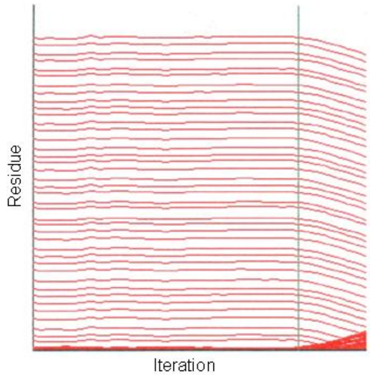

Figure 10. Residuals while iteratively re-fitting a primitive to a set of points

At a certain iteration, the residuals of the inliers increase while the other residuals decrease. This point marks the beginning of a new segment. The points already used in the found segment are then deleted from the dataset and the algorithm is repeated on the remaining points. The result of this procedure on an artificial dataset can be seen in Figure 11 in which we can clearly differentiate the two segments.

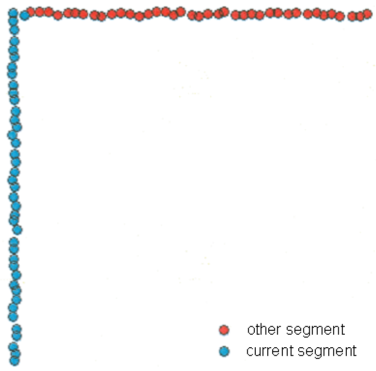

Figure 11. Artificial dataset segmented by the proposed algorithm

When the point cloud is segmented and all the primitives are fitted, the intersections of these primitives need to be computed. Therefore neighbouring clusters are searched by calculating the distances between all the endpoints of the segments. When two neighbouring clusters are found, they are either extrapolated to find the intersection or trimmed. If two segments are parallel, which can be checked based on their normals, they are marked and the user is asked to make a decision.

The result of the complete algorithm was tested on a real point cloud coming from a scanning campaign of a historical building (the Kadoc Chapel) in Leuven, Belgium. The scans were made using a Leica Scanstation 2 with an angular resolution of 10 mm. A detail of the 2D-line drawing reconstructed using the proposed algorithm is shown in Figure 12.

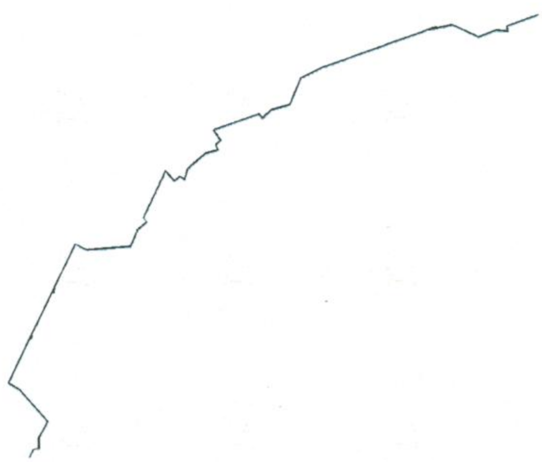

Figure 12. Detail of line and circular primitive fitting to a point cloud section of the Kadoc chapel in Leuven, Belgium.

4. CONCLUSIONS

This paper describes an ongoing research tackling many practical problems of using laser scanning in the field of heritage documentation. Firstly, the question whether laser scanners can be used for deformation monitoring was discussed. Different tests performed on a masonry arch undergoing an artificial deformation have proven that a laser scanner is able to reveal displacements of a structure of 0.8 mm which is much better than the single point precision of a laser scanner. The main factors influencing the accuracy are the campaign set-up and the proper scan resolution. For an extensive discussion of the presented case study and a more detailed overview of the accuracy of current laser scanners we refer to Demeyere and Herinckx [Demeyere&Hendrickx, 2009].

The second part of this paper discussed the automatic generation cross-sections from point clouds. A first proposal creates small line segments by cutting a point splatted 3D model of the point cloud by a plane. The resulting model is good for visualization, but lacks any topographical relation between different line segments and is thus not suitable for further processing. Therefore a more intelligent algorithm was proposed that iteratively fits 2D primitives to the point cloud section while taking into account possible noise. Tests of the algorithm on real-life point clouds of an historic structure have shown the effectiveness and level of detail that can be achieved and prove the usability of the algorithm in practice. A more elaborated discussion of this algorithm can be found in Goos [Goos, 2009]

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