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An Approach to Vector Data Extraction from 3D Point Clouds. The Paleochristian Baptistery of Santa Maria Maggiore

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Abstract

The geometry of an object can be efficiently captured using digital surveying techniques. By modelling and visualization of 3D data, it is possible to obtain vectorized information. Many users prefer to work on profiles, motivated by the need to produce two-dimensional documentation. Profiles extracted from the point clouds will inherit the noise characteristics of the original models. The application of appropriate filters can reduce this adverse effect. In general, the quality of raw data is highly dependent on the equipment performance and the survey design. This work presents an approach to the vectorization of profiles extracted from complete clouds, evaluating the potential of automatic solutions through the comparison with manually produced drawings. The discrepancy between automatically extracted contours and handheld vectorized lines highlights that the tested concave hull algorithm is able to accurately extrapolate the contours of the sectioned cloud, resulting in compression of the processing time, if the raw input data does not present serious gaps or excessive noise. Hausdorff distance between homologous models is equal to 1.66 cm, compatible with the degree of relative definition for 1:50 scale outputs, with considerable margins for improvement through optimization of the detection phases.

Keywords
close-range photogrammetry, concave hull algorithm, Hausdorff distance.

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The production of drawings in the age of digital models

In the last years, digital survey techniques have become a major source for the generation of complex building models. Some relevant advances in new technologies, the optimized detection phase, along with a reduction of instrumental cost motivate this achievement. In addition, the improvements in mapping systems (also thanks to mobile solutions) and elaboration approaches allow rising up the productivity of point cloud. Anyway, an extensive acquisition campaign is often required to guarantee a coverage of the entire surface, especially in the case of large premises. Once preliminary processing is accomplished, editing to removing background objects, the workflow to derive a consistent 2D vector draw is still a tedious job that may easily take several hours or few days, even for an experienced user. Significant manual assistance is often required for tasks such as data cleaning, gap filling, and element classification. In order to improve this process, the topic of increasing automation in the building reconstruction pipeline has been paid a lot of attention in the literature [Pu et al. 2011; Haala, Kada 2010]. However, the digital replication is generally complicated by some missing parts in the clouds. Indeed, due to time and accessibility limitations, a complete acquisition setup is not ever affordable for large scenes and you often have to get back the surface from rather imperfect raw data, i.e. noisy, incomplete and corrupted with outliers. While a careful planning of the survey can reduce occlusions in stationary applications, in mobile mapping datasets commonly a significant shadowing effect cannot be avoided due to non-removable objects along the way, overly articulated surfaces to be acquired and not always safe working conditions. All these difficulties result in an incomplete or noise-affected final model. The subsequent 2D vectorization is therefore not a mechanical process, requiring an interpretative effort supported by knowledge in the field of technical architecture and composition. Fortunately, more and more automatic solutions for the recognition of geometries are gaining ground. The point cloud vectorization consists of two fundamental phases: segmentation, which removes elements extraneous to the scene, and modelling, which reconstructs profiles. The first step is deliberately omitted here, since data in input has a good quality and needs only a few optimization operations. All the attention is reserved to the drawing, with the aim of assessing how much the automations are able to increase productivity, obviously preserving the quality of the results.

Fig. 1. Entrance to the baptistery, located to the east and protected by a *pronaos*.

Aims of the proposal and case study

In this work, we focus on the generation of cartographic documents from three-dimensional models given back through close-range photogrammetry. In particular, we analyse the performance of an automatic profile extraction algorithm, especially in the presence of imperfect and missing parts due to poor quality input data. The benchmark of our experiments is the Paleochristian Baptistery of Santa Maria Maggiore, located in the province of Salerno and specifically in the municipality of Nocera Superiore. The origin of the structure is still uncertain; scholars of the local history trace it back to a Roman temple to which, only after the insertion of the pool, a Christian function would be given [Pecoraro 1994]. The Baptistery is circular in plan. A masonry cylinder plastered in yellow –in which eight round arched windows open, with a pavilion roof covering the upper part of the dome– rises from a lower concentric body, which has a sloping roof. As a result, from the outside you can perceive the internal articulation of the spaces, divided into a central hall and a perimeter nave, but you cannot imagine the domed and the vaulted ceilings. On the western side, from the circular gallery –whose frame turns at the same height– protrudes a horseshoe shaped apse, with a window on the axis and two foreparts on the sides; the latter reach only two thirds of the height and suggest two niches, now walled. To the east, there is a protruding *pronaos* (fig. 1). This, open on three sides, has a square plan and is covered by a canopy supported by four square pillars. Above, at the height of the cornice of the annular corridor, there is a two-sloping roof. All this protects the entrance. Once you cross the threshold, the interior appears far more solemn and complex than the simple external form, which is not very harmonious in the proportions of the elements, especially the windows. Unlike the exterior, the original structure is almost intact, with a few additions at the back. A ring of fifteen pairs of columns, each joined to the next by a round arch, circumscribes the internal space covered by the dome, separating it from the circular barrel-vaulted gallery; at the centre of it opens a pool with an octagonal profile, framed by single columns (fig. 2). Such an articulated structure is the perfect benchmark to evaluate the capabilities of the selected concave hull algorithm. This contour-based solution (opposed to intensity-based solutions that convert points into input into images) uses edge identification and tracking. The primary purpose is to quantify the time contraction of the design process and the overall quality of the output data through comparison with a handmade homologous draw (fig. 3).

Fig. 2. The pool with an octagonal profile, framed by single columns.

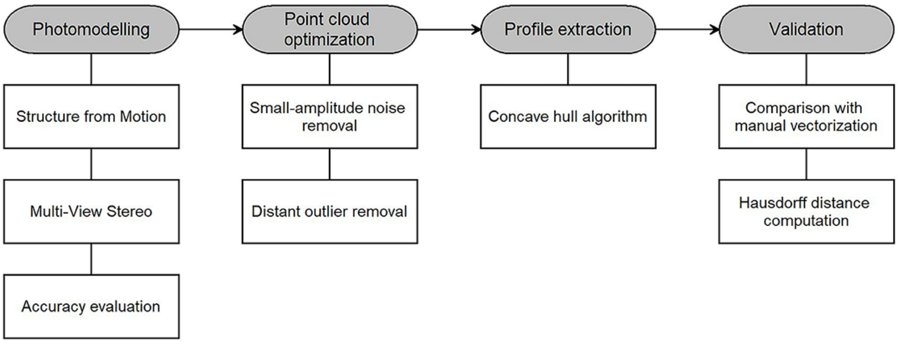

Fig. 3. Block diagram of the proposed methodology.

Photomodelling for architectural survey

One of the most widespread techniques for heritage documentation is photogrammetry. This solution outlines a rather wide panorama, with practical and partly theoretical differentiations. Specifically, our application uses digital and analytical close-range photogrammetry [Sužiedelytė-Visockienė et al. 2015; Morena et al. 2017] (fig. 4). If the geometric model of the forward intersection always represents the theoretical basis, the use of a computer speeds up the whole process. It can be divided into two fundamental parts: the orientation of the images, with the so-called Structure from Motion, which allows the collimation in monoscopy of several frames, and the dense image matching, often defined as Multi-View Stereo. The ground control points (GCPs), indispensable for the resolution of the collinearity equations during orientation, are acquired by means of a TCRA 1102 Plus Leica total station. It guarantees an angle-measuring accuracy of around 0.3 gon and a distance one of 3 mm + 2 ppm on up to 80 metres, without using reflectors. Ten GCPs are employed, suitably distributed in the scene. The processed dataset includes about 400 frames, acquired with a Nikon D750 camera in FX format (pixel pitch = 5.95 μm), with a size of 24.3 MP and a focal length of 35 mm. The acquisition pattern consists of converging camera axes, typical of unconventional terrestrial photogrammetry. The model obtained has a resolution of 6.60 mm per pixel (GSD) and a reprojection error of less than 0.96 pixels for all tie points.

Fig. 4. Longitudinal cut-section (A-A') of the photogrammetric point cloud.

Point cloud optimization

Generally, noise of a point cloud can be classified as small-amplitude noise and distant outliers [Schall et al. 2005; Zaman et al 2017; Wolff et al. 2016]. The first one has the points randomly distributed around the surface. In the distant outliers, clusters are away from a true surface. Several methods are available for noise removal, specific to the characteristics of the analysed data. A geometric-based filter is used for this benchmark (fig. 5). The algorithm locally fits a plane through each point in the dataset, which is based on neighbours extracted by number or a kernel radius search method. Subsequently, if the distance of the point from the fitted plane is greater than the threshold known as the maximum error rate, the element is removed. This threshold can be defined in absolute terms or in relative ones, as a factor of the neighbour reprojection error on the fitted plane. Due to the way the code works, it is very powerful on flat surfaces (walls etc.). However, especially if you use a too high kernel radius (or too low inaccuracy threshold) it will 'eat' the corners. In order to save the corners or sharp edges it is advisable to run the algorithm repeatedly with a small radius and relatively high error threshold.

Concave hull algorithm for profile extraction

For the automation of the cartographic production, we test the capabilities of a concave hull algorithm [Wang, Cho 2015; Soltaninejad et al. 2016]. The input data are represented by horizontal slices of the point cloud, extracted by defining the height of a plane and an offset to it. The technique used to compute concave hulls is based on nearest neighbour, kernel functions, using a convex hull. The code starts from the convex hull of the sliced points. The only parameter to set is the maximum size of a single edge, if possible. If an edge is longer than the specified value, the algorithm will try to split it by using another point nearby. This way the contour will fit the cloud more tightly. Therefore, the smaller the parameter is, the tighter the draw will be.

Comparison with the traditional approach to vectorization

In order to make a performance analysis on the tested algorithm, the automatically extracted profile is compared with completely hand-drawn homologous outline. For a global evaluation, Hausdorff distance is employed [Zhang et al. 2017].
Assigned a metric space X and two subsets $A, B \subseteq X$, the following quantities are first introduced. The distance of a point from the set A is

$$d(x, A) = \inf_{y \in A} d(x, y).$$

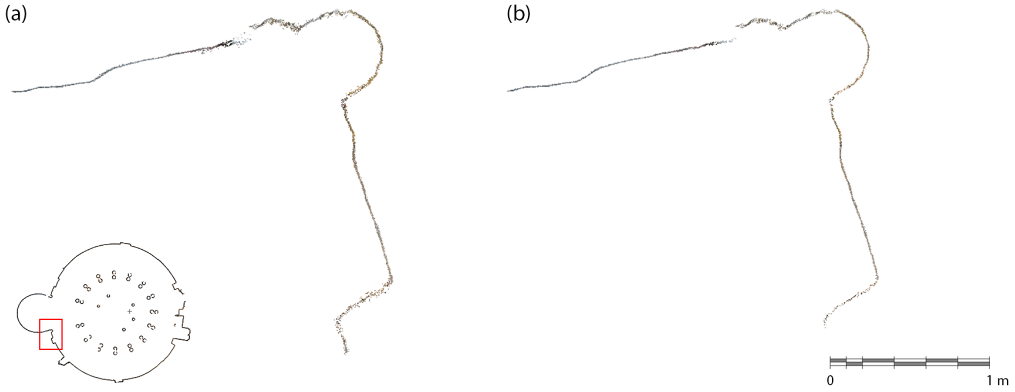

Fig. 5. Detail of the point slice of before (a) and after (b) optimization.

It is then defined as surplus of A over B the quantity

$$e(A, B) = \sup_{x \in A} d(x, B).$$

At this point, we define Hausdorff distance between A and B as the quantity

$$d(A,B) = \max[e(A,B), e(B,A)].$$

This metric represents the greatest of all the distances from a point in one set to the closest point in the other set. Unlike the minimum distance, it is able to quantify the spatial configuration differences between morphologically complex objects such as CAD polylines (fig. 6).

Comparison

Data employed to verify the capabilities of the concave hull algorithm come from the dense cloud of the baptistery, generated with photogrammetric technique. In detail, a 5 cm thick slice is extrapolated at 1.20 m from the internal walking surface. It has a mean surface density of 25000 points per square meter (about one point every 6 mm). The global comparison between homologous models gives a value for the Hausdorff distance equal to 1.66 cm, compatible with the degree of relative definition of the graphic reduction scale 1:50. The latter, equal to 2.50 cm, is obtained as the ratio between the denominator of the reduction ratio and the minimum objective dimension of the line in the drawing on paper (0.05 cm). In other words, the discrepancy between the two profiles, the one drawn (A - fig.7) and the one automatically extracted (B) are not perceptible in the 1:50 scale printed work. It is interesting to note that the value of the surplus of B over A is slightly higher than that of A over B (tab. 1). This is a sign of a more regular profile A than that of B, the automatic algorithm being partly sensitive to the noise of the input cloud.

Table 1 - Statistics of distances between handmade (A) and automatically extracted (B) profile.

Distance from	min	surplus	mean	RMS
A to *B* (cm)	0.00	1.43	0.17	0.20
B to *A* (cm)	0.00	**1.66**	0.18	0.21

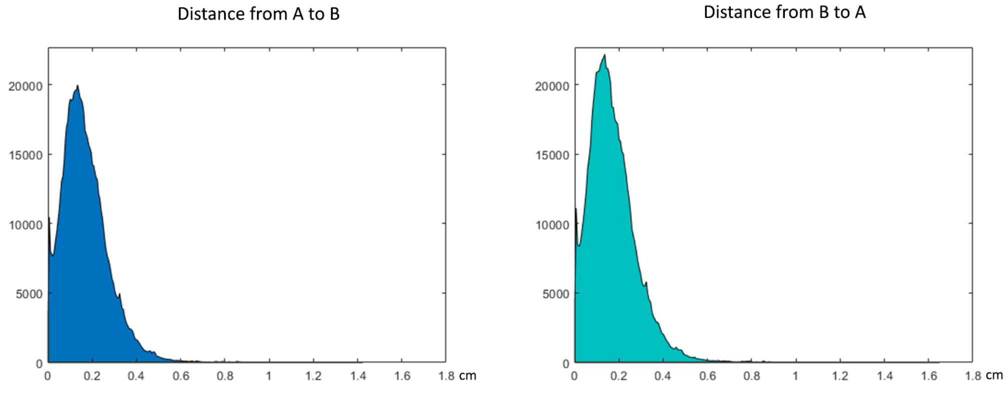

Fig. 6. *Distribution of distances between the two analysed profiles.*

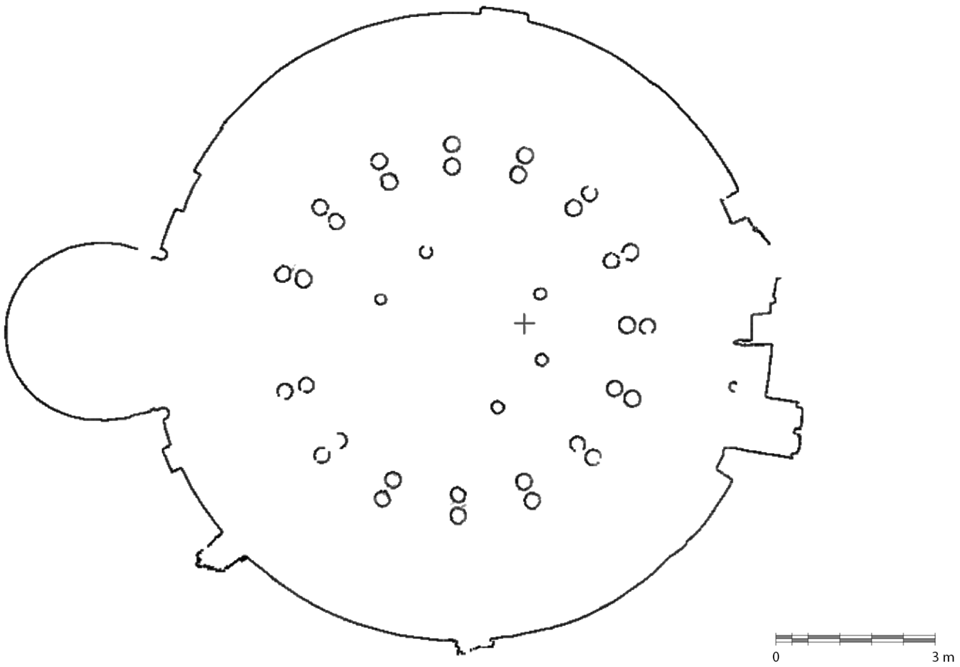

Fig. 7. Profile *B*, automatically extracted with concave hull algorithm.

Environmental occlusions, missing parts and edge preservation

Analysing the slice extracted from the global model it can be observed that the twin columns separating the tunnel from the central part represent one of the most critical areas in the acquisition phase. This is due to the spatial configuration of these elements, responsible for numerous occlusions. It is precisely at this point that the algorithm manifests its limits, being unable to extrapolate geometries when the available data is not sufficient. If for a flat surface this inconvenience is easily overcome, this is not possible in the case of curved surfaces, such as columns. Another indicator of the algorithm capabilities is to analyse the shape reconstruction in the points where several surfaces converge. Here, in fact, it is more likely that there are gaps or low-quality data depending on the acquisition pattern. The tests carried out only show good recognition of geometries where there is a sufficient number of frames capturing the area of interest. Failure to do so will result in a summary or incomplete detection.

Conclusions

Increasing the efficiency of vectorization processes for cartographic drawings is of fundamental importance today. Nodal issues are time compression and support for the extrapolation of geometric features. Particularly interesting is the concave hull algorithm tested here. Its strong point is the ability to accurately identify shapes, provided that the raw input data does not present large gaps. These, in fact, affect the vectorization and require the operator to intervene retroactively to remedy them. More critical are the curved areas. As far as edge preservation is concerned, the analysis highlight that the code is able to accurately reconstruct the geometries if the area of interest is acquired through an appropriate number of frames. The global comparison between homologous profiles (hand drawn and automatically extracted) shows a discrepancy, quantified by Hausdorff distance of 1.66 cm. This implies that in a 1:50 scale representation on paper the difference is negligible. However, it should be noted that there is ample room for improvement, strictly dependent on the quality of the raw input data. The greatest strength of the automatic process is the compression of working time. Using the same point slice an operator needs within 110 minutes for a vectorization in AutoCAD, against the few seconds required by the concave hull algorithm. In addition, there is the time necessary to verify the correctness of the results, not exceeding a few minutes. Starting from these observations, future work will be oriented to the broadening of the open source algorithm with a segmentation module, aimed at further streamlining the vector drawing workflow. Equally important is the need to fill the gaps found in the extrapolation phase of the geometries, bearing in mind that it is particularly difficult (and not very convenient from an economic and temporal point of view) to obtain a complete model in every detail during the acquisition step, even if starting from an optimal survey design. The illustrated procedure therefore highlights the possibility of using automated systems for the generation of complex surface profiles, thus acting as a good practice in verifying the congruence between the real trend and the one inferred from the point cloud. Finally, the results achieved show how this approach can lead to interesting cultural implications, in terms of documentation and knowledge of the architectural heritage under investigation, optimizing the execution time but at the same time ensuring a remarkable geometric and morphological reliability about the nature of the surfaces to be represented.

Fig. 8. Axonometric view of the baptismal font from point cloud.

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