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Evaluation of the Expected Data Quality in Laser Scanning Surveying of Archaeological Sites

Mattia Previtali[1], Lucia Díaz-Vilariño[2], Marco Scaioni[1], Ernesto Frías Nores [3]

[1] Politecnico Milano, Dept. of Architecture, Built Environment and Construction Engineering, via Ponzio 31, 20133 Milano, Italy, {mattia.previtali,marco.scaioni}@polimi.it
[2] Universidade de Vigo, Dept. of Design in Engineering, Campus Lagoas-Marcosende, Vigo, 36310, Spain, lucia@uvigo.es
[3] Universidade de Vigo, Dept. of Natural Resources and Environmental Engineering, Campus Lagoas-Marcosende, Vigo, 36310, Spain, efrias@uvigo.es

***Abstract* – Laser Scanning is nowadays more and more widespread for documentation of archaeological sites. To guarantee a proper survey, especially in the case of large archaeological site, several parameters need to be taken into consideration to guarantee the effectiveness of the documentation. In particular, these account for data accuracy, density and completeness. Generally, scan planning is empirically based on the personal experience of the operator. This paper presents a more controllable and reliable way for scan planning optimization. The presented methodology is based on a two-step approach. In the first step, starting from a preliminary plan of the site to be surveyed, a ray tracing algorithm is applied to a set of scan point candidates and finally the scan position optimization is based on a backtracking algorithm, considers a minimum scene coverage as stopping criterion. In the second step, starting from the previously defined positions, scans are simulated to derive the expected scan accuracy, density and completes. The presented methodology is tested on two archaeological sites the 'Grandi Horrea' of Ostia (Italy) and the 'Basilica di Massenzio' in Rome (Italy).**

I. INTRODUCTION

Three-dimensional surveying of Cultural Heritage sites has become today a quite standard step in the documentation process. Structure-from-Motion Photogrammetry and Laser Scanning are the two basic approaches to provide point clouds which can be adopted in real sites, while other techniques are limited to laboratory applications (e.g., close-range ranging techniques).

The focus in this research has been given to Laser Scanning (LS), which is particularly efficient when operating in complex environments. Indeed, the presence of complex areas and surfaces that should be surveyed from inside, as well as the need of measuring both control and check points [1], makes generally, the use of photogrammetric techniques more complex for the documentation of large archaeological sites. Not to mention that the large amount of data may determine processing overload in the image orientation and dense matching phases [2].

The recent development of portable dynamic laser sensors working on the basis of SLAM techniques [3] is particularly suitable for the documentation of large areas in a short time. Indeed, the possibility of survey an area while walking through it reduces significantly the data acquisition phase. On the other side, the accuracy of such approach is still significantly lower than the one that can be obtained from static LS.

Today, due to the previously listed reasons, LS is the technique that is mainly used for documenting large archaeological sites. Indeed, the automation in data acquisition and registration lowered the entry barriers and increased the number of users. However, to guarantee the effectiveness of the LS survey a set of parameters has to be taken into consideration. Among the different survey requirements, data accuracy, density and completeness are the key parameters to be addressed. For this reason, a careful scan planning is crucial for the final quality of the survey to accomplish.

In the most cases, planning the instrument standpoints when using static Terrestrial Laser Scanners (TLS) is a task that is empirically based on the user experience. However, a more reliable and controllable methodology is needed to guarantee the effectiveness of the survey. Díaz-Vilariño et al. [4] have demonstrated that the knowledge of the approximate geometry of an archaeological place can be exploited to support the use of numerical methods to help the decision about TLS standpoints. A deep preliminary analysis may contribute to save time during field work and to guarantee a better coverage of the surfaces to be recorded.

Here this approach is further extended to include a simulation of LS data acquisition, following an initial hypothesis that can be obtained from empirical or machine-supported planning. A tool for simulating different types of LS data "Heidelberg LiDAR Operations

Simulator" (HELIOS - https://www.geog.uni-heidelberg.de/gis/helios.html) developed at the University of Heidelberg (GIScience Research Group, Germany) has been adopted to this purpose [3]. Both planning and simulation of LS data are operated thanks to the availability of a rough model of the site to survey

After the simulation of laser scanning data, the successive step is the evaluation of the quality of the "virtually" collected point cloud. On the basis of this results, the planning of TLS standpoints and data acquisition parameters might be revised (Fig. 1).

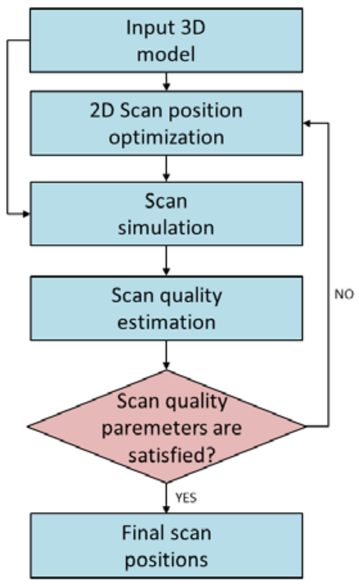


Fig. 1. Workflow presented for planning optimal locations of laser scans.

II. PLANNING OF TLS STANDPOINTS

In [4] and [6] an automatic method to optimize the number and position of standpoints for TLS has been proposed and validated. The aim of this approach is focused to obtain a high-quality point cloud in terms of data completeness. The minimization of the number of scans results in a reduction of the estimated surveying time and the decimation of redundant data, and as proven, this is of special relevance for large areas such as outdoor archaeological sites.

The input of the method is a floorplan in which elements are organized in layers according to their class, allowing to plan the acquisition for certain archaeological elements. This method starts by the creation of an occupancy map in order to determine the navigable space in which the acquisition system can be placed. Next, the navigable space is discretized into candidate scan positions according to different patterns such as grids, triangulations or tessellations. In order to evaluate the suitability of each candidate, a visibility analysis based on a ray-tracing algorithm (see [7]) is applied to all candidates, obtaining the theoretical area of the archaeological site that would be scanned for each candidate position. Finally, optimization is carried out by using a backtracking algorithm, which considers a minimum scene coverage as stopping criterion.

The algorithm based on the generation of candidate scan positions within a triangulation-based distribution is shown to perform better with regard to a grid-based distribution.

This approach was previously tested against two real case studies in Italy and Spain, respectively, which showed the applicability of scan planning to large archaeological sites. Since the method is designed for 2D analysis, completeness is also estimated from a 2D point of view, giving only an initial estimation of the quality of data acquisition.

III. SIMULATION OF TLS DATA USING HELIOS

While the methodology described in Section II can provide a preliminary optimized distribution of TLS standpoints, an additional analysis of the potential point cloud to be obtained can be used to access the data quality of 3D data acquisition. In order to operate this task, the software HELIOS has been used here.

The main inputs for the simulation with HELIOS are: (i) laser scanner typology and scanner parameters, (ii) definition of the area to be scanned, and (iii) definition of the scanning positions/paths.

First, the software requires the definition of the scanning platform (Terrestrial, Airborne or Mobile LS) and the definition of the characteristics of the scanner (e.g., range accuracy, beam divergence, pulse frequency, etc.). In a scanning project several scanners can also be used and/or scanning parameters can be changed between different scans.

Second, a model of the area to be simulated has to be provided. A rough model can be used for evaluation the expected data quality in laser scanning data acquisition. To derive a preliminary model of the area that needs to be scanned several strategies can be adopted: (i) digitalization of existing documents, (ii) a low-quality model derived from a preliminary survey, (iii) re-use of existing data sets.

Finally, HELIOS requires the definition of the scanning positions, in the case of TLS, or the scanning paths, if ALS or MLS are set. In the presented work TLS standpoints are derived from the planning strategy presented in the previous section.

IV. POINT CLOUD QUALITY EVALUATION

While several studies have been published about the quality assessment of some specific phases of LS surveying (see, e.g., [8]), the evaluation of the quality of the final point cloud is a complex task. Even though the specific 3D surveying technique(s) employed may influence the final data quality, the error budget does not depend only upon the adopted methodology. Consequently, the discussion hereafter is also valid when SfM Photogrammetry is used [9].

Three main aspects should be carefully considered:

1. *3D point accuracy*, which refers to the correct spatial location of a point cloud, i.e., the distance between the "surveyed" and "true" points;
2. *Point density*, which provides the amount of points recorded to approximate the surface of an object; and
3. *Point completeness*, which considers the presence of missing parts in the captured object.

In the following subsections, the methodology adopted to assess each of the three aspects listed above is briefly discussed in the case of TLS surveying.

A. 3D point accuracy

In a real TLS survey, the accuracy depends on three main factors: (a) absolute georeferencing; (b) scan co-registration; and (c) precision of 3D points.

In a simulated point cloud, we assume that no bias exists in the surveyed data sets, and the positional errors on 3D points can be derived by propagating errors in georeferencing/registration and in intrinsic measurements. Assuming a variance-covariance of the input parameters, using a simple geometric model the respective variance-covariance of the output 3D coordinates can be computed [10].

When operating with SfM Photogrammetry, this method is more difficult to be applied, especially to account for the precision related to dense surface matching stage. An interesting approach was proposed in [11].

B. Point density

The evaluation of point density is important to guarantee that the recorded point cloud has a sufficient resolution to reconstruct all the details of the investigated site. It's important to distinguish the density of the point cloud from the density of the modelled surface (e.g., using TIN or other types of surface approximations). If we consider a planar triangular surface, for example, three points at the corners are enough to define a triangle that models the object. But if we consider the point cloud we would like to obtain, points are also needed on the flat surface.

According to this concept, the point density should be locally evaluated on the surface within a prefixed diameter around each point, as proposed in [12]. This metrics can be depicted on the approximate model of the object to depict the point density distribution that can be obtain from the proposed data acquisition plan. A minimum threshold for the local point density is established to check whether this parameter may be accepted or a revision of the scan plan is needed.

C. Point completeness

Point completeness refers to the fact that the full surface of the investigated object is surveyed and represented in the point cloud. Lack of completeness is typically due to occlusions during scanning. In the case this problem is due to the incomplete acquisition, an improvement of the scan standpoint planning may overcome it. On the other hand, it should be considered that in the reality the presence of moving objects or vegetation may also result in lack of completeness, which cannot be foreseen during the planning stage.

The evaluation of the point completeness can be done by comparing the rough model of the site with a mesh model computed on the basis of the simulated point cloud. A maximum size for the triangular meshes should be selected to avoid triangles that do not correspond to real surfaces.

V. EXPERIMENTAL RESULTS

The presented workflow was tested on a couple of case studies. The first one is a portion of the so called "Grandi Horrea," which were the ancient public food storage (mainly crop) of the city of Ostia Antica, Italy. Not much of the building remains, except for the remains of the foundation walls and some blocks of tufa (Fig 2a). The second one is the "Basilica di Massenzio". It is one of the largest building in the Roman Forum and last basilica built in the ancient Roma (Fig 2b).

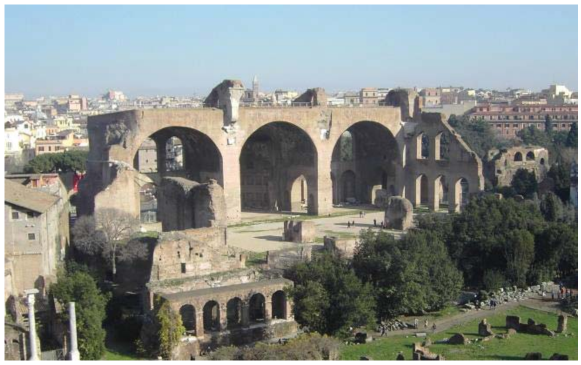

a

b

Fig. 2. The "Grandi Horrea" of Ostia Antica (a) and the "Basilica di Massenzio" (b), Italy.

Data acquisition with a phase-shift laser scanner FARO FOCUS X330 was simulated to scan these archaeological sites. Table 1 shows the parameters used for the planning of TLS standpoints, while Table 2 shows the results including point cloud completeness and number of TLS standpoints. Due to its complexity, parameters used for planning the acquisition in “Grandi Horrea” are smaller than parameters selected for “Basilica di Massenzio.” In both cases, triangulation was selected as the pattern for distributing candidates to scan positions. It should be noted than the navigable space in “Basilica di Massenzio” is restricted to the indoor site of the Basilica. For this reason, completeness is lower than 75%. The output of the simulation is shown in Figure 3.

As a result of the optimization, 98 standpoints were defined for the “Grandi Horrea” and 16 standpoints for “Basilica di Massenzio.” The high number of standpoints for the “Grandi Horrea” is due to the large number of different rooms characterizing the site.

Table 1. Parameters used in planning of TLS standpoints.

	“Grandi Horrea”	“Basilica di Massenzio”
Maximum ange[m]	10	20
Distance security [m]	0.8	2
% completeness for walls	75	75

Table 2. Simulation results for two case studies.

	Grandi Horrea	Basilica di Massenzio
# TLS Standpoints	98	16
Point completeness	75.07	65.92

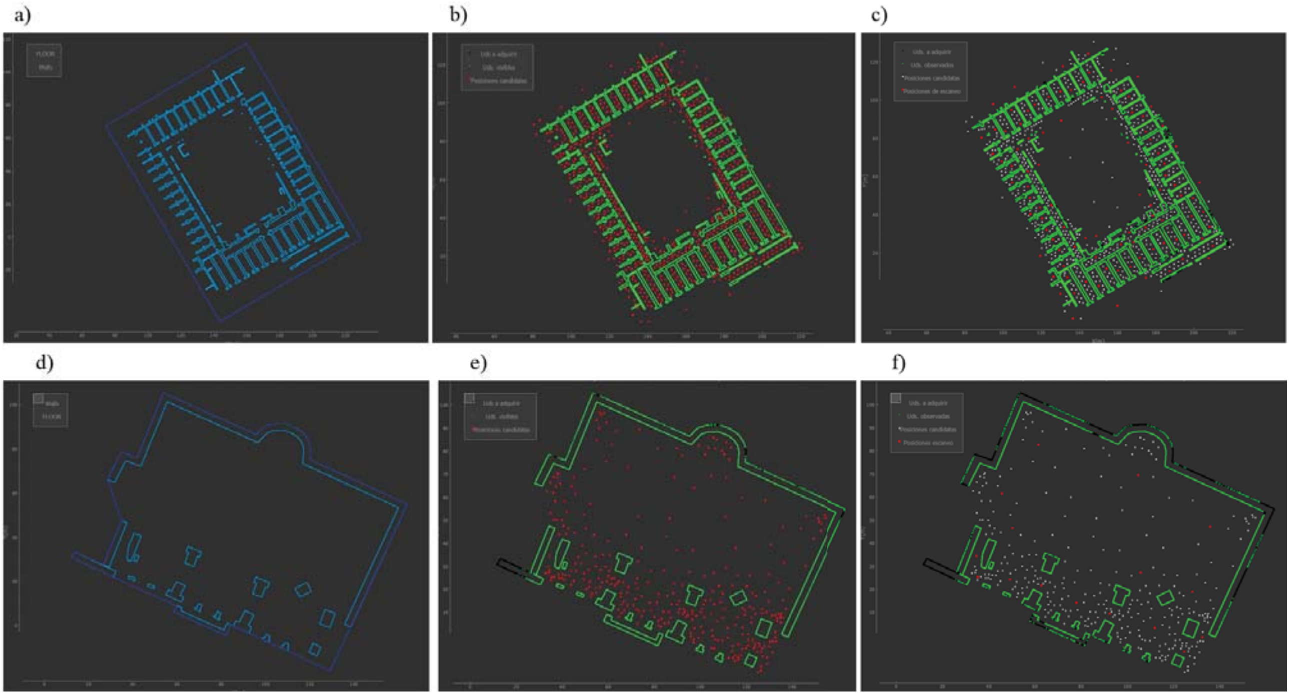


Fig. 3. Simulation results for the two case studies “Grandi Horrea” (a-b-c) and ‘Basilica di Massenzio’ (d-e-f). On the leftmost column, subfigures a-d show the input layers consisting on walls and floor representing the navigable space. In the centre, subfigures b-e show the candidate scan positions (in red) according to a triangulation-based distribution (b-e). On the rightmost column, subfigures c-f show the results after the optimization stage: in red the final TLS standpoints and in green the coverage of the scene.

The parameters used for scanning are reported in Table 3. In particular, the vertical resolution was set at 0.43° while the horizontal one was set at 0.28° for all the scans in both case study. The scanner is supposed to be mounted on a tripod at a high of 1.5 m with respect to the ground at each standpoint.

The approximated model of the area to be surveyed was derived in two different ways for the two sites. For the “Grandi Horrea”, OpenStreetMap (OSM) was used to derive the 3D model of the area. In particular, the open-source converter OSM2World was used to create 3D models of the area from OSM data. For “Basilica di Massenzio”, a low-resolution photogrammetric model, derived starting from Google Maps 3D®, was used as input to model this area. The obtained 3D mesh models were also used to define the 2D site plans for the two sites. Even if in the presented case studies the plans were derived manually, they could be also obtained in automated way starting from the mesh models.

Table 3. Scanning parameters used in both simulations.

FARO FOCUS X330	
Range accuracy [m]	0.002
Beam divergence [rad]	0.00019
Pulse frequency [Hz]	100,000
Pulse length [μs]	4
Wavelength [μm]	1550
Vertical Field-of-View [deg]	300
Horizontal FoV [deg]	360
Scan frequency [Hz]	120
Scan rotation velocity [deg/sec]	10

The Output of the simulation are summarized in Fig. 4 and in Table 4.

Table 4. Point cloud quality evaluation for two case studies.

	"Grandi Horrea"	"Basilica di Massenzio"
# Scanpoints	97	16
Number of points	~90 million	~16 million
3D point accuracy	92.24 %	94.58 %
Point density	73.76 %	88.35 %
Point completeness	52.19 %	58.21 %

Point accuracy was computed by comparing the simulated point clouds with the input scene and by considering the fraction of points having a dicrepancy lower of ±5.0 mm.

Point density represents the percentage of points having a number of neighbours lower than 100,000 in a circle with radius 0.57 m.

The point completeness is computed subdividing the input scene into voxels of size 0.1 m and computing if they are occupied or not by simulated scan points.

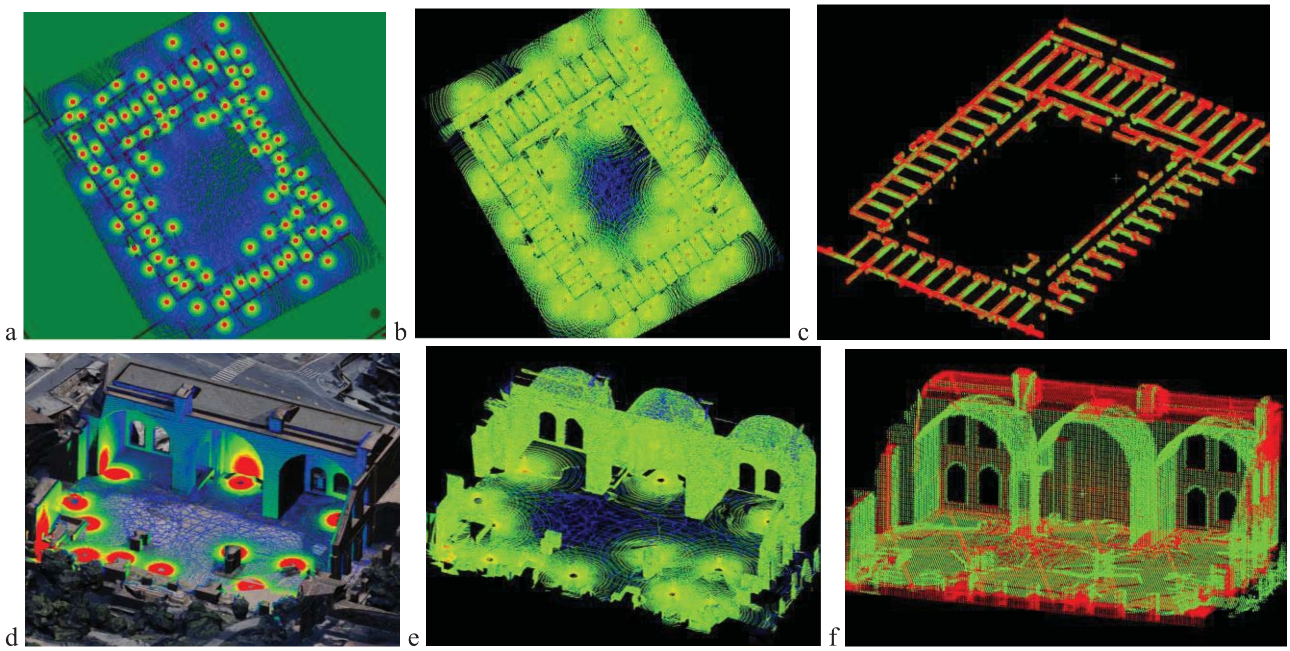


Fig. 4. Results in terms of scan quality of the simulated point clouds for the case studies "Grandi Horrea" (a-b-c) and "Basilica di Massenzio" (d-e-f). On the leftmost column, subfigures a-d show the point clouds where points are coloured according to point density (red-higher, blue-lower). In the central column, subfigures b-e show the point clouds where points are coloured according to the estimated 3D point accuracy, which was evaluated on the basis of the discrepancy from the original model. On the rightmost column, subfigures c-f show the voxelized point clouds where voxels are coloured according to point completeness (green voxels are surveyed while red voxels are not).

Concerning scan completeness it can be observed the difference between the one that it estimated in the 2D scanpoint optimization and the one derived from the symulation. This difference has some specific explanations connected with the specificity of the two sites. In the case of the "Grandi Horrea," the top part of the walls was not surveyed, reducing this way data completeness. This outcome was due to the mounting of the adopted TLS at an high of 1.5 m. Mounting it in a higher poistion could increase the completeness of the final model. In the case of the "Basilica di Massenzio," the topmost part of the Basilica cannot be surveyed from the ground due to some self-occlusions of the building.

VI. CONCLUSIONS

Careful scan location planning and a-priori quality evaluation of results are activities generally neglected when conducting a laser scanning survey. However, in the case of large projects they can play a relevant role for a successful survey. This paper presented a methodology for evaluation of the expected data quality in laser scanning acquisition to be used for driving the selection of the laser scanning standpoints in the case of archeological sites. Three main parameters are analyzed: 3D point accuracy, point density and point completeness. The effectiveness of the proposed method was tested in two case study, the "Grandi Horrea" (Ostia, Italy) and the "Basilica di Massenzio" (Rome, Italy). The flexibility of this method was proved in two completely different scenarios. Indeed, while the case of the "Grandi Horrea" is characterized by a set of small spaces, "Basilica di Massenzio" is a large unique space. In addition, the latter case study is a fully 3D complex building with high barrel vaults. The proposed simulation can be carried out only if a preliminary 3D model of the entire archaeological area is available. In many cases a model can be obtained from web-available data set, as in the case of the case study presented in this paper. In the case such a data set is not available a preliminary 3D model can be obtained either by using existing and ancient drawings or by performing a UAV survey of the area. We have also to mention that the proposed method can be in some cases quite time consuming for large sites, especially in the simulation phase. For example, the "Grandi Horrea" simulation took approximately 12 hours on a standard personal computer. However, it has to be noticed that it is mainly computational time and optimization in the implementation could significantly speed up the computation.

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