Geometric Modelling of a Large Dam by Terrestrial Laser Scanning

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Key words: Terrestrial Laser Scanning, Large Dam, Surveying, 3D Modelling

SUMMARY

This paper presents an experience of terrestrial laser scanning surveying of a large dam located in Alta Valtellina (Italy) at the Cancano Lake. The handler of this plant (AEM S.p.A., Milan) has requested this activity to produce some drawings of it – which was built up during ’50 – and to construct a 3D model to be used as geometric basis for the finite-element modelling of static and dinamic structural behaviour. In the paper all stages of the process for data acquisition are described; in particular, large enphasis is given to the information extraction stage needed for the setup of final documents. Moreover, some notes about a method to compute the accuracy of surface points which have been measured by terrestrial laser scanning are reported.

RIASSUNTO

L’articolo presenta un’esperienza di rilevamento mediante laser scanner terrestre di una grande diga situata in Alta Valtellina (Italia) presso il lago di Cancano. Il concessionario dell’impianto (AEM S.p.A., Milano) ha infatti richiesto questo tipo di intervento per realizzare alcuni disegni di consistenza dell’opera - risalente agli anni ’50 - e per costruire un modello 3D della stessa da utilizzarsi come supporto geometrico alla modellazione ad elementi finiti del comportamento strutturale di tipo statico e dinamico. Nell’articolo vengono descritte tutte le fasi del processo di acquisizione ed elaborazione dei dati, con particolare riferimento all’estrazione delle informazioni necessarie per la redazione dei prodotti finali. Inoltre vengono fornite alcune indicazioni sulla modalità per determinare la precisione di acquisizione dei punti di una superficie rilevata con strumentazione laser scanner.

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1. GEOMETRIC SURVEYING OF LARGE DAMS

Monitoring the structural behaviour of large dams has always been a topic of great importance, due to the impact these structures have on the whole landmark where they are built up. In particular in the last two decades the evolution of computing techniques has introduced the possibility of very accurate mathematical modelling of static and dinamic problems concerning dams. However, these techniques require a detailed geometric reconstruction of the dam structure as well as of the terrain in its nearby. Unfortunately, construction plans and project drawings are available only for dams built up in recent years, not for the oldest ones – which generally are just those presenting major structural problems!

Traditionally the topographic surveying of large dams is performed by the integration of geodetic and photogrammetric techniques. The first ones are used for the measurement of the geodetic network and for the acquisition of details; the others for deriving surfaces of dams as well as related buildings and structures. Furthermore, the use of aerial photogrammetry would allow to acquire a DTM of the whole area. This approach is strongly limited by the huge number of points needed to describe all surfaces of a dam, resulting in a very large waste of man-time. Even though automatic techniques of digital photogrammetry could theoretically speed up the process, in reality these cannot be successfully applied in the most cases due to the lack of texture typical of concrete structures, resulting in the failure of image matching algorithms.

On the other hand, the appearance of *Terrestrial Laser Scanning* (TLS) during the last decade has introduced a new chance in dam surveying. The capability of acquiring big point clouds in a short time, the high degree of automation (at least at the data capture stage), the accuracy and the long range of current instruments make this technique really competitive with respect to the others, which are used to get complementary data (see Pfeifer & Lichti, 2004 for an oveview about this subject). Moreover, laser scanners allow a 3D dense modelling which could be used by structural engineers to implement more refined mathematical methods to study the dam behaviour. Up today, the computation of static and dinamic response under external sollicitations has been carried out by approximate methods (e.g. *finite-element modelling*- FEM, see Zienkiewicz & Taylor, 1989) based on a geometric dam's model derived from digitalization of design drawings (i) or by geodetic measurements (ii). In both cases, the global 3D model features a low point density (in the order of about 1 point every 1÷2 m^2) and a spatial accuracy ranging from ±10÷20 cm if method (i) has been used and ±5÷10 cm with method (ii). These characteristics make this kind of 3D models really suitable for classical mathematical modelling, but in case you want to compare real deformations of the structure to external environmental (temperature, sun radiation, etc.) and load conditions (level of water in the basin), such 3D models are no more enough. Whatever you need are accurate dense models which can be quickly acquired at different times during the year in correspondence of significative variations of boundary conditions. Currently these kinds of data can be achieved by optical instruments and automatic displacement sensors positioned on the dam structure, which give accurate measurements however limited to a small number of controlled points. From this consideration, the reader may easily understand somehow the use of TLS technique could give an important contribute to this field, because it is capable to acquire accurate and dense point clouds describing the dam surfaces. Moreover, data capture can be performed in a relatively short time, as shown in the case study reported in this paper.

2. A PRACTICAL APPLICATION AT THE CANCANO DAM

2.1 Finality

The interest about the use of laser scanning to acquire data for FEM is currently growing up, as proved by different papers on this topic concerning architectural buildings (Guarnieri *et al.*, 2006) and industrial structures (Ioannidis *et al.*, 2006). Among these, applications to large dams have recently begun to be investigated (Schneider, 2006), being this subject very fascinating for the size and the complexity of the environment where they are usually built up.
The occasion to focus on this problem has arisen from a cooperation between Politecnico di Milano and AEM S.p.A.[1] Production Area (Grosio, Italy) finalized to setup an experimental laser scanning approach for monitoring dam displacements (first results will be reported in Alba *et al.*, 2006). Motivated by the need of a FEM analysis of the Dam of Cancano Lake, in the middle of famous touristic villages of Bormio and Livigno (Valtellina, Italy), AEM S.p.A. encharged Politecnico di Milano of the laser scanning surveying to provide the geometric models of the dam.

In the sequel of the paper, after a presentation of the dam, all the procedure for data capture and processing will be shown. In particular this paper has the finality to show an example for TLS surveying of big structures based on criteria for evaluation of the accuracy and for a correct design of the data acquisition, aspects that up today have been under-evaluated in practical applications.

2.2 The Dam of Cancano Lake

The dam of Cancano Lake has been built up in ’50 on the Adda river, generating a basin of about 124 million m^3 of water (Fig. 1). In the area there is another artificial lake (San Giacomo) bounded by a dam, resulting in two consequent basins with a difference of full supply level of about 100 m.

The dam presents an arc gravity structure featuring 136 m of height and 381 m of length at the crest. The conservation of the structure is good, thanks to the monitoring which is carried out by traditional sensors (strain gauges, inclinometers, etc.) and by periodical geodetic measurements (levelling and geodetic control networks, optical collimators).

[1] AEM S.p.A. is currently the main facility management company of Milano city.

The morphology of the ground is really suitable for laser scanning surveying, because the valley presents the shape of a natural arena just in front of the dam. Thank to a lift, very comfortable positions for TLS stand-points can be easily reached.

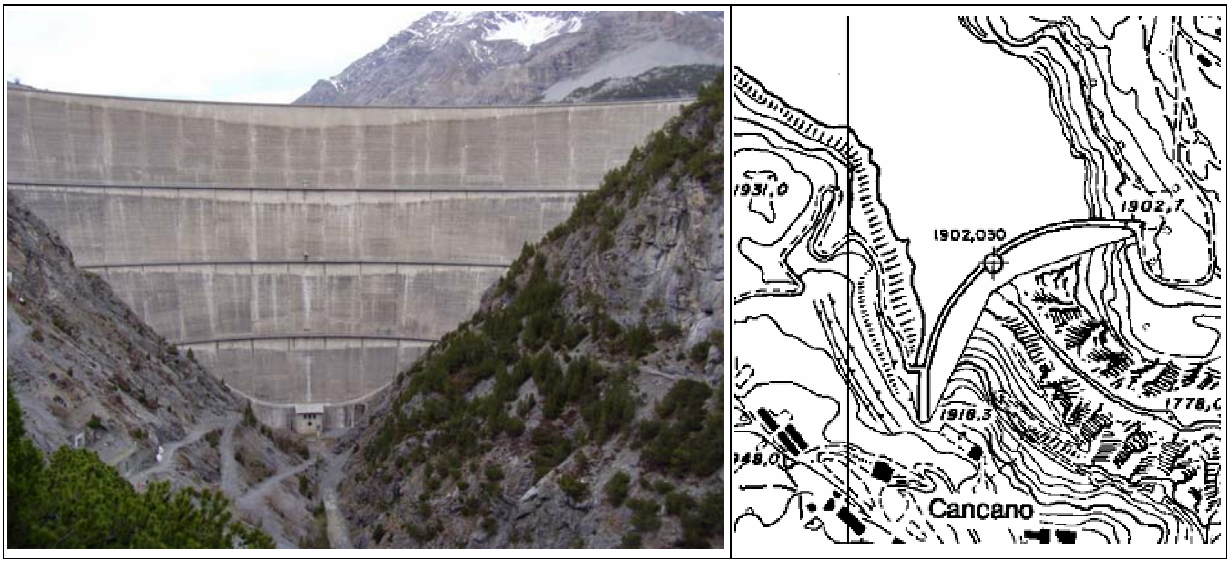

Figure 1: on the left a frontal view of the dam of the Cancano Lake, on the right a topographic map of the site.

2.3 Instruments

The laser scanning surveying has been carried out by adopting a Riegl LMS-Z420i equipped by a calibrated digital camera Nikon D100 (6.1 Mpixel) and by a tool for the tilt-mounting. This device has been used because the horizontal FoV of this scanner is panoramic (360°), but the vertical one is limited to ±40°. Thanks to the knowledge of the relative transformation between all tilted positions of the scanner head and the vertical one, the georeferencing procedure is quite simple. Once the LMS-Z420i has been georeferenced in vertical position by measuring enough GCPs, all tilted positions will result georeferenced as well. In a similar way, also the integrated digital camera is mounted in a known position, so that all acquired images can be oriented in the *Intrinsec Reference System* (IRS[2]) of the scanner in a straight-
A detailed description of technical features of this long-range TLS can be found at Riegl website; a good review is reported also by Ingensand (2006).

For the sake of completeness, two Leica total stations have been used: a TCA 2003 for the measurement of geodetic network and a TCRA 1203 for the determination of GCP coordinates and for some detail measurements.

[2] In Scaioni (2005) the description of reference systems adopted in this paper is reported.

2.4 Design of Laser Scanning Surveying

Requirements of the AEM S.p.A. indicated a complete surveying of external surfaces of the Dam of Cancano Lake, barring those covered by the water of the basin and including a wrap of rock of about 50 m of length just off the dam. To get such data, 10 main scan positions have been established, as shown in the layout reported in Figure 2. From each stand-point, apart a few exceptions, 2 or 3 different scans have been acquired according to different inclinations of the Riegl LMS-Z420i head. As can be seen in Table 1, reporting some parameters for each scan, at the end of the measurements from main stand-points, further 16 small scans have been acquired to fullfil lacking parts. This fact shows somehow the planning of laser data acquisition is a really complex task, requiring an a priori rough 3D model to correctly plan all scans to get.

Each scan has been integrated by its companion digital images captured by Nikon D100 camera equipped by a 20 mm lens.

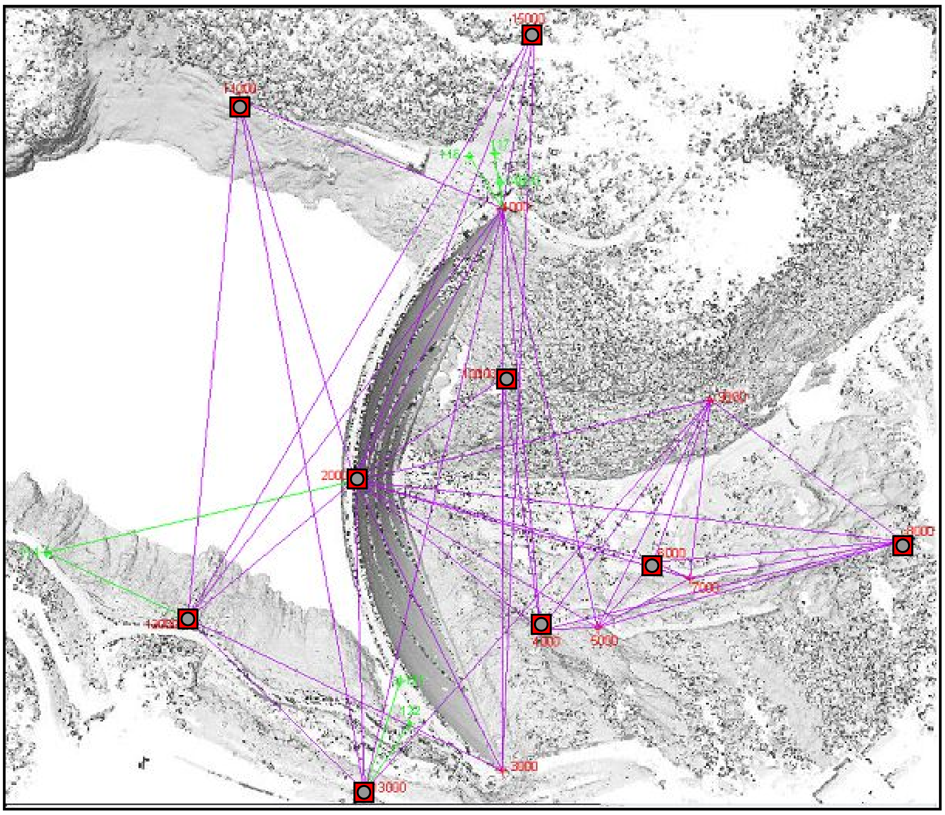

Figure 2: planimetric view of the dam of Cancano Lake, reporting the layout of the geodetic network and the main laser scanning stand-points.

2.5 Georeferencing of Sans

The strategy adopted for scan georeferencing is based on the use of GCPs materialized by different kinds of targets (see par. 2.5.2). Coordinates of these have been measured in the *Ground Reference System* (GRS) from vertices of the geodetic network (see par. 2.5.1). This solution is due to a threefold motivation: the shape of the dam, consisting in two portions (down and up stream faces) which should be independently registered by means of GCPs, being impossible the use of *surface matching* techniques because of the very poor overlap; the panoramic horizontal FoV of Rielg LMS-Z420i, allowing the target measurement all around the scanner stand-point; thank to a relatively small set of GCPs that could be viewed from different positions, many scans could be georeferenced. At this stage the instrument has been placed over a topographic tribrach put on a tripod, that in main stand-points has been centered over a vertex of the geodetic network. This fact has allowed to determine the position of the IRS center into the GRS, so that this could be used as further GCP. To keep vertical the *z* axis of the IRS, a level plummet fixed to the scanner head has been used. Finally, the Riegl LMS-Z420i has been tilted from the vertical position to acquire inclined scans at some fixed angles; this capability results in enlarging the vertical FoV. The geometric relation between the IRS of the scanner in vertical and tilted positions can be modelled by a 2D roto-translation, whose parameters have been computed by means of a field calibration.

Stand-points	***# of scans for each stand-point***	***Scanning time [min]***	***# of total measured 3D points (Mil)***	***Mean point density on the object [points/cm]***	***Acquisition range [m]***		***FoV [deg]***		***Angular resolution [deg] H & V***
					max	***min***	***V***[3]	***H***	
2000	3	7	2.8	0.01	106	200	43	72	0.05
4000	2	10	5.2	0.05	100	250	68	69	0.01
6000	1 multi-scan	26	11.6	0.05	157	220	50	37	0.01
8000	1 multi-scan	19	10.2	0.05	283	317	23	27	0.01
10000	2	9	3.9	0.05	56	230	72	75	0.01
11000	3	23	3.6	0.01	140	330	17	61	0.03
12000	2	15	3.7	0.01	100	281	26	99	0.04
13000	3	12	4.4	0.01	59	300	38	85	0.04
14000	1	2	0.7	0.01	2	43	76	66	0.20
15000	2	8	1.3	0.01	115	427	16	27	0.03
Detail scans	16	34	11.2	0.01	2	50	-	-	0.10

Table 1: features of scans acquired by Riegl LMS-Z420i at the Dam of Cancano Lake.

2.5.1 Geodetic Network

In the nearby of the dam a geodetic network established during the dam construction already existed. However, due to the bad conservation of its monuments, a new network has been setup and measured, consisting in 11 main vertices materialized by topographic nails fixed in concrete elements on the ground. The geodetic network is the materialization of the GRS.
The measurement has been carried out by means of a Leica TCA2003 total station. The least squares adjustment of the geodetic network has resulted in the determination of 3D points with estimated standard deviations of ±2 mm in X-Y and ±3 mm in Z. Coordinates of some points belonging to the old network have been measured from the new one, in order to integrate existing plans of the dam into the current laser scanning surveying. Similarly, thank to static GPS measurement, 2 points of the national GPS network IGM95 has been linked to

[3] Here the vertical FoV coming from all scans acquired at the same stand-point is considered.

the local network, in order to derive cartographic coordinates of points in the Gauss-Boaga grid[4].

2.5.2 Ground Control Points

Three kinds of GCPs have been adopted, all consisting of targets covered by retro-reflecting paper. The type (a) is made up of an alluminium disk (ϕ = 120 mm) with a reflecting circular shape (ϕ = 100 mm), fixed in permanent way to the concrete surface of the dam or to some stable rocks in the nearby (see Fig. 3a). These targets have been positioned in May 2005 for the experimentation about monitoring of dam's displacements. Sixtytwo of them have been placed on the dam front as control points, while other 10 around stand-points 6000 and 8000 to define a permanent reference system. Indeed, from these points all scans used for monitoring purpose have been acquired. The availability of GCPs (a) has allowed the precize georeferencing of all scans imaging the down stream face of the dam.
Other two kinds of targets are cylinders of circular section, built up in two sizes to be used according to the scanning range: type (b) features diameter ϕ = 50 mm and height h = 50 mm (Fig. 3b); type (c) ϕ = 100 and h = 100 mm (Fig. 3c). The advantage of these targets is the possibility of putting them directly over known points by a tripod or a a pole without a permanent materialization. They have been distributed all around TLS stand-points focused to capture the upstream face, the crest and some details of the dam.

Figure 3: different targets used as GCPs

Generally, the criterium adopted to plan GCP positioning is to have at least 5 points per scan placed at different elevation and horizontal angle around the scanner stand-point. The measurement of coordinates of GCPs in the GRS has been made by stationing over some vertices of the geodetic network with a total station Leica TCRA 1203. In case of targets (a), they have been determined by multiple angular intersection from points 5000, 7000, 9000 and 10000, obtaining a st.dev of ±3 mm in X-Y and ±4.5 mm in Z. In case of targets (b) and (c), the measurement has been made by substituting the target with a topographic prism, which has been measured from the geodetic network.

2.6 Data Acquisition

All scans needed for the geometric modelling have been acquired during a 3 days measurement campaign on September 2005. Both georeferencing and point cloud capture has been controlled by the software Riscan Pro licensed by Riegl and installed on a PC linked to the scanner. The electrical supply has been provided by a portable generator Honda EU 10i,

[4] In Mugnier (2005) a description of the Italian geodetic datum is reported.

capable of a 0.9 kW power for 13 kg of weight. In Figure 4 is reported the adopted laser scanner and its tools during a data acquisition stage.

The TLS has been positioned on each stand-point as described at par. 2.5. The first operation to carry out is the measurement of GCPs, which is always performed at the highest resolution in both horizontal and vertical directions, disregarding the specific resolution selected for the scan (see Table 1). The approximate positions of targets where a dense scanning should be performed can be found in two ways:

Figure 4: laser scanner Riegl LMS-Z420i with its tools during scanning of the dam downstream face.

1. by *automatic* extraction from a preliminary panoramic scan at low resolution: by exploiting the high reflectiveness of retro-reflecting targets, all points that figured out an intensity over a threshold are selected as approximate positions for candidate target points. This process may fail in case targets are too far from the TLS, so that the signal for automatic localization in the panoramic scan becomes two low. Once all targets have been measured into the IRS, correspondences to points in GRS can be automatically found;

2. the second method requires to introduce the approximate GCP positions by the user, after the direct georeferencing of the laser scanner into the GRS. Then the measurement process goes ahead as with method (1).

At dam of Cancano both methods have been used, considering that the position of many targets was already known at the surveying time.

After the GCP measurement the scan can be started. This stage require the definition of the scanning window and the angular resolution, which should be properly selected to avoid the acquisition of too much observed points. While the windowing has been carried out in order to completely cover the dam surface and the near surroundings, the resolution has been setup to guarantee a minimum density of 1 point/100 cm^2 for the farest portion of the scan. This adoption has resulted in a higher real resolution, considering that many points are at shorter range and that several areas of the dam have been captured from different stand-points. The size of laser beam-width, according to the adopted distances, is ranging from 6÷12 cm considering a measurement range between 200÷400 m; in reality, the inclination of the incidende laser ray with respect to the normal of the measured surface would enlarge the laser beam-width. However, considering that the shape of the Cancano dam is featuring very poor discontinuities along the range direction, the influence of laser beam-width on the precision of 3D point measurement is quite low.

Each scanning has been integrated by the capture of enough colour images in order to cover the whole point cloud. The pixel size on the ground resulted in the range 15÷20 cm.

2.7 Data processing

The first stage of data processing is to compute the georeferencing of all scans based on the measurement of targets in each scan. This task has been firstly performed by the Riscan Pro SW and then verified by a software developed by the users in order to make more refined analysis about accuracy. The least squares computation of 3D roto-translation for each scan has resulted in a sigma nough about ±1 cm, according to a number of 4-8 GCPs per scan. Exceptions have been done for scans covering the dam front, where all targets of kind (a) adopted for monitoring have been used for the geometric surveying as well. In these cases, even higher accuracies have been obtained.

Secondly, each scan has been pre-processed in order to manually remove parts not needed for 3D modelling. At this stage alla scans could be put together to get a 3D model of the Cancano dam and its surroundings at the acquired resolution. Unfortunately, the large amount of point (about 59 million points) has prevented to manage them as a whole because the large occupation of memory in the computing machine. As a consequence, two ways have been followed according to the kind of products to derive. For generation of 3D models, each scan has been filtered in order to reduce the amount of points. For the derivation of drawings (plans and cross-sections) the original data have been processed separately for each scan (or by grouping a few scans), as shown at next paragraph.

2.8 Derived products

As introduced previously, 3 different sets of products have been derived from the laser scanning surveying. The first group consists on a set of drawings aimed to document the dam geometry:

- planimetric maps of dam and its surroundings (scale 1:500);
- vertical cross-sections drawn in the middle point of each structural sector of the dam;
- inclined cross-sections drawn in corrispondence of junctions between adjacent structural sectors on the dam downstream face;
- horizontal cross-sections drawn at prefixed heights;
- ortoprojections of both faces of the dams;
- vector front views of both faces of the dam.

The second group collects all the stuff needed for the mathematical modelling of structural behaviour of the dam:

- global 3D models of the whole dam structure and of rocks all around this for an extention of about 50 m, generated at different spatial resolutions;
- 3D models of the most important structural sectors of the dam concerning FEM analysis.

Finally a third group of products consists on 3D photo-textured models for visualization purpose at different scales.
In the following some notes about the process adopted to derive different products are reported.

2.8.1 Derivation of 2D drawings

The tecnique adopted to derive 2D drawings is based on the used of data at the highest resolution without any filtering process. This means that different scans have been processed separately or grouped into small sets. At the end of information extraction, all derived data have been fused together. All this stage has been performed by importing all georeferenced data into the software Polyworks InnovMetric ver. 9.0, where the information extraction has been performed. At the end, these have been imported into Autodesk Autocad Map 2005 for the final editing.

The derivation of the general planimetric map at 1:500 has been carried out by extracting horizontal cross-sections at an interdistance of 0.50 m, that have been used to draw contour lines. Missing objects have been added up by manually interpreting the 3D point cloud and by means of direct measurement on the ground by a total station Leica TCRA 1203.
In a similar way, horizontal and vertical cross-sections have been generated by fixing the intersection planes at desired positions. More complex has been the generation of sections along the curve lines defined by junctions between adjacent sectors on the dam's front. This task has required to approximate each curve junction line by several planes and to joint together all portions of cross-section.

Finally, the derivation of both up and downstream face front views has been accomplished by vectorization of corresponding ortoprojections. The vectorization of the prospect requires the interpretation of many details, such as junction lines between concrete sectors, boundary of rock covering blocks, discontinuities between dam and rock, and so on. An operator has to carry out this task, but the direct interpretation of the point cloud is usually quite difficult. The use of ortoprojections derived from a DSM based on laser scanning measurements and from digital imagery acquired by the integrated camera simplifies the vectorization of prospects without a large loss of accuracy.

In figure 5 the process to derive the frontal prospect is summarized. Firstly, the point cloud covering all this face has been shared into 3 groups, in order to reduce the amount of data to manage, and imported in the software Polyworks. Each point cloud, already georeferenced and cleaned up from not necessary points, is triangulated to derive a TIN (Fig. 5a). The colour images captured by Nikon D100 calibrated camera are directly oriented in the GRS, because the camera exterior orientation in the IRS of the scanner is a priori known. The generation of the ortoprojection can be then performed in a straight-forward manner, without any supplementary photogrammetric task to do (Fig. 5b). Finally the ortoprojection is manually vectorized (Fig. 5c) so that the front view can be extracted and then edited in Autocad Map.

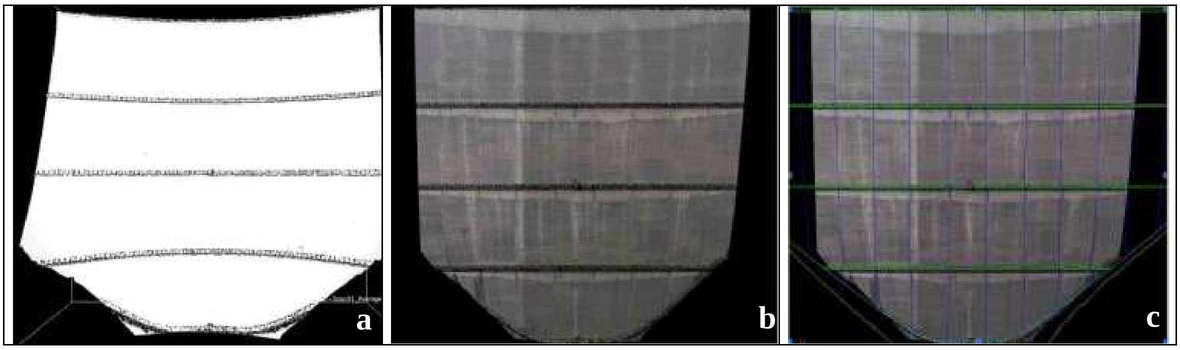

Figure 4: process to generate a vector prospect of the central portion of the dam downstream face (from left to right): triangulation (a), ortoprojection (b), vectorization (c).

2.8.2 Derivation of 3D models

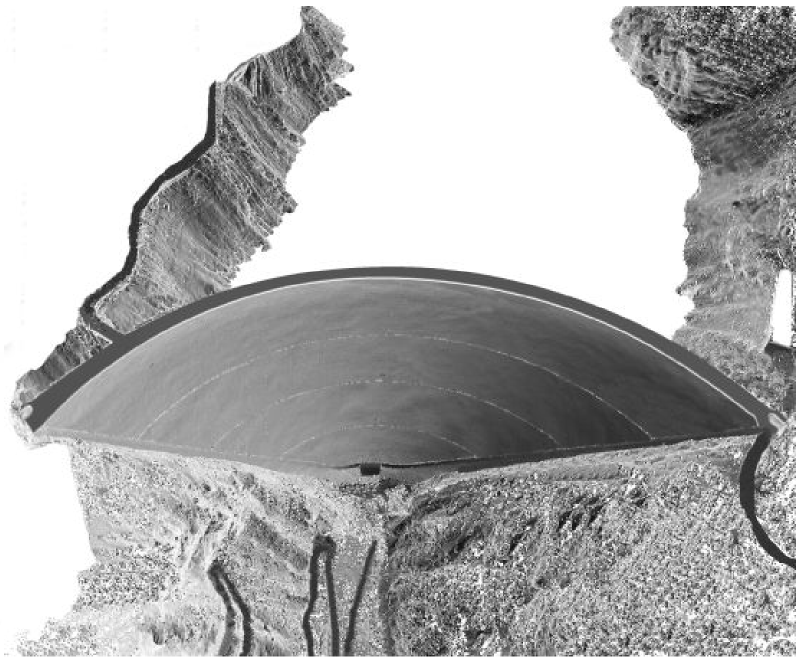

Figure 6: visualization of 3D model of the surrounding area of the dam of Cancano Lake in grayscale coloured version.

The purpose of 3D models to derive is twofold: to yield a geometric model for FEM modelling (i); to generate some photo-textured realistic models for vizualization at different scales (ii).
The group (i) has been derived by spatial filtering of the original point cloud, obtaining a regularized point density along X, Y and Z axes. Four different models have beed produced, according to a step of 20, 50, 100 and 200 cm in all directions. Different data sets would allow the selection of the most suitable geometric model for mathematical modelling purpose. The adopted filtering tecnique is quite rough, because is not considering the presence of break-lines and discontinuities of 3D models, and because it performs a spatial decimation of points without looking at the normal direction of surfaces. The use of a more refined adaptive filtering technique would be worthwhile.

The group (ii) of 3D models have been derived for a realistic vizualization of the dam and its surroundings. Two solutions have been adopted. The first one refers to a 3D model of the dam structure, based on a point cloud filtered at a density of 1 point/0.25 m^2 and then triangulated. Thank to the digital images acquired during the TLS surveying this model has been photo-textured. Furthermore, by using all acquired scans, a general point cloud of the whole area of the dam and the basin at a density of 1 point/1.00 m^2 has been generated (see Fig. 6). To avoid of increasing the amount of data, this model has not been triangulated but the colour derived from the corresponding digital image has been assigned to each point. However, this simple technique is enough for global vizualization at low scale. The integration of terrestrial laser scanner data to airborne LIDAR data and imagery would allow to get a very complete 3D model of that area.

3. EVALUATION OF THE ACCURACY IN SURFACE MEASUREMENT

The evaluation of the accuracy is very often omitted in laser scanning surveying, especially in practioners' activities. On the contrary, in the survey planning both aspects of completeness and accuracy should be fulfilled by theoretical and methodological tools. Furthermore, because the real accuracy of TLS data might depend on a large error budget, techniques for its empirical evaluation after data acquisition and processing are worth. In next paragraphs, methods for the evaluation of accuracy before and after the surveying of Cancano dam are described.

3.1 Theoretical Accuracy

The theoretical evaluation of the accuracy which can be obtained from laser scanning data is a quite complex problems, because it depends on metrological aspects of the adopted instruments (Ingensand, 2006), on georeferencing (Gordon & Lichti, 2004), on the material (Lichti & Harvey, 2002) and on the incidence angle of laser beam to the surface of scanned object (Bae *et al.*, 2005). Considering results reported in literature, errors due to latest two factors are really difficult to quantify. For a preliminary analysis of uncertainty, we have included in the error budget only contributes coming from intrinsic measurements and georeferencing.
The expression of the uncertainty for a scanned 3D point can be evaluated as reported in Scaioni (2005):

$$\mathbf{C}_X = \mathbf{J}_{geo}\mathbf{C}_{geo}\mathbf{J}_{geo}^T + \mathbf{J}_{int}\mathbf{C}_{int}\mathbf{J}_{int}^T \qquad (1)$$

where $\mathbf{C}_{geo}$ is the covariance matrix of georeferencing parameters and $\mathbf{C}_{int}$ that of measured quantities. In the covariance propagation formula (1) $\mathbf{J}_{geo}$ and $\mathbf{J}_{int}$ are derivative vectors derived from geometric relations to transform georeferencing parameters and intrinsic measurements into 3D point coordinates.

The expression of $\mathbf{C}_{geo}$ depends uniquely on the geometric position of GCPs and on their uncertainty, so that a preliminary estimate of it could be carried out for each scan. Covariance matrix $\mathbf{C}_{int}$ can be evaluated as follows, considering the standard deviations of measurements (range σ_ρ, horizontal and vertical angles σ_α and σ_θ) and the laser beam cross-section δ_b:

$$\mathbf{C}_{\text{int}} = \text{diag}\left(\frac{\sigma_\rho^2}{m}, \sigma_\alpha^2 + \frac{\delta_b^2}{16}, \sigma_\theta^2 + \frac{\delta_b^2}{16}\right) \quad (2)$$

where *m* is the number of scan repetitions in case multi-scan is adopted.

For each planned stand-points at Cancano dam the $\mathbf{C}_{geo}$ matrix has been computed, while a unique $\mathbf{C}_{int}$ has been setup, except scans 6000 and 8000 where a multi-scan approach has been used (m=4). Different covariance matrices $\mathbf{C}_X$ of scanned points have been evaluated for the most critical sets of angular positions. Even though these results are only approximations, they may give an address about the expected uncertainty of scanned points.

3.2 Empirical Acuracy

To evaluate the empirical accuracy of acquired point clouds is a task almost complex to solve, due to the difficulty in finding other measurements as reference. An evaluation of the quality of georeferencing has been already presented at par. 2.7, when residuals on GCPs have been analysed. However, this test is made on targets, which are measured in a more accurate way than other scanned points. Further analyses concerning some other independent control targets which have not been used as GCP have confirmed similar results.

The approach used to access the accuracy of not-target points cloud is based on the analysis of the overlap area between different scans covering the same portion of the dam structure. By operating in the software Polyworks, point belonging to a pair of scans (9000 and 4000) of the downstream face of the dam have been compared with the criterium of looking for the shortest point in a radium of 50 mm. The mean of shortest distances between the nearest points of different scans is resulted 14 mm, with a st.dev. of $\pm$ 10 mm. The total amount of 130932 analyzed points has shown RMS of distances of 17 mm, which is compatible with all tolerances expected for products of this TLS surveying.

4. FINAL CONSIDERATION AND GUIDELINES FOR FUTURE APPLICATIONS

In this paper an experience of laser scanning surveying of a large dam located in Northern Italy has been presented. The finality of this project was to provide geometric data for FEM of the structure and to get related by-products such as 2D drawings (planimetric map, cross-sections, frot views, ortoprojections) and VR 3D models.

The adopted solution has resulted in a fast data acquisition (3 days for TLS and 2 days for geodetic network establishement and measurements), and in the high quality of all products.

This application would call for the interest on the use of this approach to improve the study of the statical behaviour of large dams. Data derived from laser scanning are very accurate and dense, so that they could be used for even more refined analysis. Moreover, this experience has shown the need of close cooperation between surveyors and structural engineer, which must define whatever they expect from TLS surveying. This integration would avoid the error of acquiring more data than necessary in some portion of the structure where the regularity of surfaces enables the geometric modelling on the basis of a small number of points. On the contrary, might exist areas close to the structure itself (e.g. rock faces) which devises to be studied for their geomorphological and geomechanical properties, which have been excluded from data capturing.

Considering a possible diffusion of this kind of application, a keynote is addressed to national autorithies and institutions dealing with large dam surveillance and security. Laser scanner surveying is expected to become a standard for all important dams, and laws should be consider this. On the other hand, technical regulations must be provided to avoid that unprepared companies will deal in the future whit this task. In particular, the analysis and the evaluation of accuracy is strictly important, as shown at chapter 3 of this paper.

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