

Terrestrial Laser Scanner and Close Range Photogrammetry point clouds accuracy assessment for the structure deformations monitoring

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Key words: Terrestrial laser scanner, close range photogrammetry, displacements, SfM, point clouds modelling

SUMMARY

In this paper we show the results of several tests carried out using methods and instrumentation typical of an architectural survey, along with a set of metrological instrumentation, on a Reinforced Concrete (RC) beam subjected to increasing loads. The goal was to assess the accuracy in the displacements estimated by a medium quality terrestrial laser scanner (TLS) Focus 3d from Faro Technologies, and the low-cost digital camera Canon PowerShot S110 used in a Close Range Photogrammetry (CRP) survey. The software used for scan-data and point clouds processing was Reconstructor JRC Software v. 3.1.0, maintained by Gexcel Ltd, while the images processing was performed with the software Photoscan from Agisoft, which implements Structure from Motion (SfM) approach. Two processing strategies were used in the point clouds comparison: mesh2mesh and modelling the beam behavior fitting the contours of the beam with second order polynomials.

Comparisons between the TLS and CRP techniques and the metrological equipment used in parallel highlighted the limits and potentialities of the two geomatic techniques used. It has been shown that modeling the behavior of the beam leads to significantly better results than using the mesh2mesh comparison. For the CRP the increase in accuracy was in the order of 40%, while for the TLS of 50%.

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1. INTRODUCTION

The recent event of the “Ponte Morandi” collapse raised again the need in Italy for the monitoring of road infrastructures or even old historical structures to save the assets and ensure adequate safety levels. In the same way the last earthquake near Amatrice made ruins of hundreds of houses leaving a couple of firemen with the task of declare accessible the houses still standing.

In order to handle the problem, we need to make accessible, to more engineers than a few high skilled technicians, instrumentation and surveying methods able to estimate structural deformation with enough reliability to guarantee a correct interpretation of structures behavior. To this end we wonder if the new surveying instrumentations, as ultimate Terrestrial Laser Scanners (TLS), together with user friendly new software based on Structure from Motion (SfM) algorithms, used in Close Range Photogrammetry (CRP), able to return the 3d model of even very complex compounds [1], could be used not only to generate realistic 3d model, but even to give information as overall damage, cracks aperture or amount of displacements. The last information, indeed, spanning from a few tenths of a millimeter to several millimeters or even few centimeters, is more in the field of metrology, or in the specialized high precision geodetic surveying than in architectural surveying [2]. Nevertheless, in this paper we put the question “What confidence can we put on the metrical component of 3d models?” or “is it possible to infer information about the stability of a building picking some points on the 3d model and comparing them with a reference state or a CAD model?” The answer is highly dependent on the combination of instrumentation used to make measurements, the specific software and the strategy applied in displacement assessment [3].

To give an answer we did several tests using methods and instrumentation typical of an architectural survey, along with a set of metrological instrumentation, on a Reinforced Concrete beam subjected to increasing loads. The goal was to assess the accuracy in the displacements estimated by a medium quality terrestrial laser scanner Focus 3d from Faro Technologies, and the low-cost digital camera Canon PowerShot S110. Both equipment return dense point clouds from which information can be retrieved. The software used for scan-data processing was Reconstructor JRC Software v. 3.1.0, maintained by Gexcel Ltd, while the images processing was performed with the software Photoscan [4] from Agisoft, which implements Structure from Motion (SfM) approach [5].

2. INSTRUMENTATION

The aim of this work is to test the accuracy and precision achieved with a Terrestrial Laser Scanner (TLS) and a low-cost CRP system, for the measurements of structure displacements.

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Thus, several bending tests were developed on Reinforced Concrete (RC) beam in the Large Model Pavilion of the Department of Civil, Environmental Engineering and Architecture (University of Cagliari) Materials Laboratory. The adopted concrete is characterized by a cubic compressive strength of 30 MPa. The beam cross section, the reinforcements distribution and the test scheme can be seen in Figure 1. The RC beam was subjected to four points bending test. The load was applied by a hydraulic jack with incremental steps from 0 to 68 kN. Three metrological equipment were used to measure displacements:

- two displacement transducers (DT) that convert rectilinear mechanical motion into a variable electric signal that can be digitally recorded. Their nominal displacement is 100 mm, nominal sensitivity 2 mV/V, sensitivity tolerance $\pm 0.1 \%$, measure resolution 1 μm
- the Laser Tracker Leica AT402 (LT) characterized by an uncertainty in the coordinates (UXYZ) of $\pm 15 \mu\text{m} + 6 \mu\text{m/m}$ (Maximum Permissible Error).
- The Aicon Moveinspect DPA system with camera Nikon D3x (DPA) with a nominal measurement accuracy of $2 \mu\text{m} + 5 \mu\text{m/m}$ (RMS), or $3 \mu\text{m} + 7 \mu\text{m/m}$ (3σ).

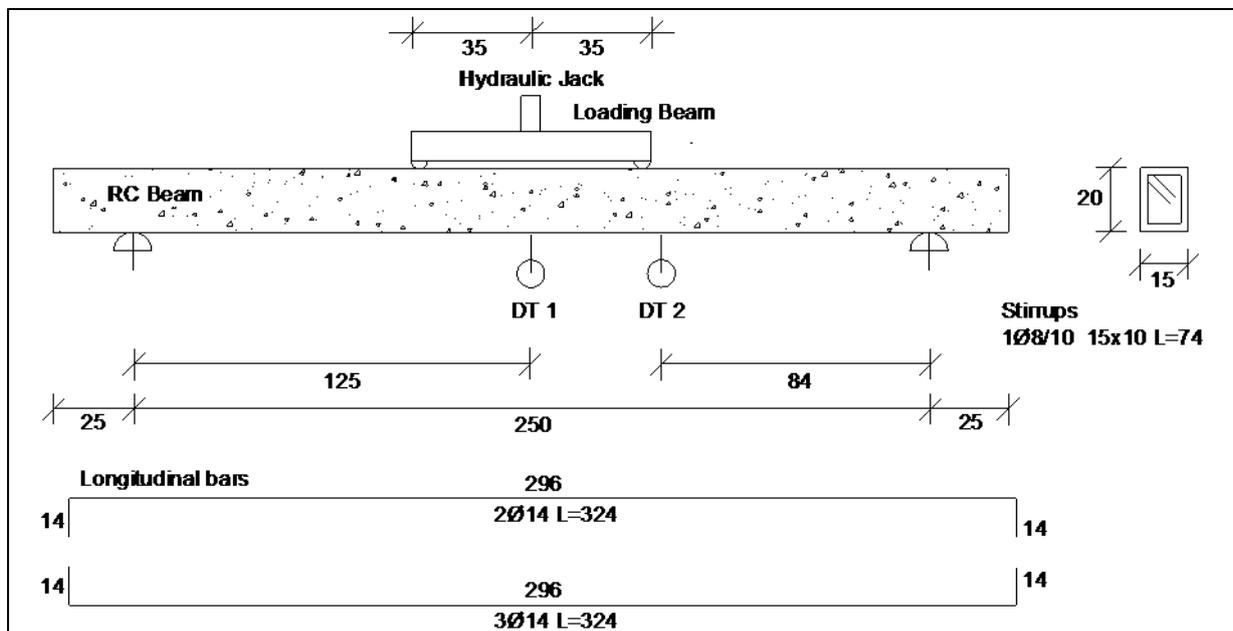


Figure 1: Test set-up

The DTs, applied under the beam as shown in Figure 1, were able to measure vertical displacements, while Laser Tracker and the Vision Metrology System together measured three dimensional displacements on a very large set of points shown in Figure 2.

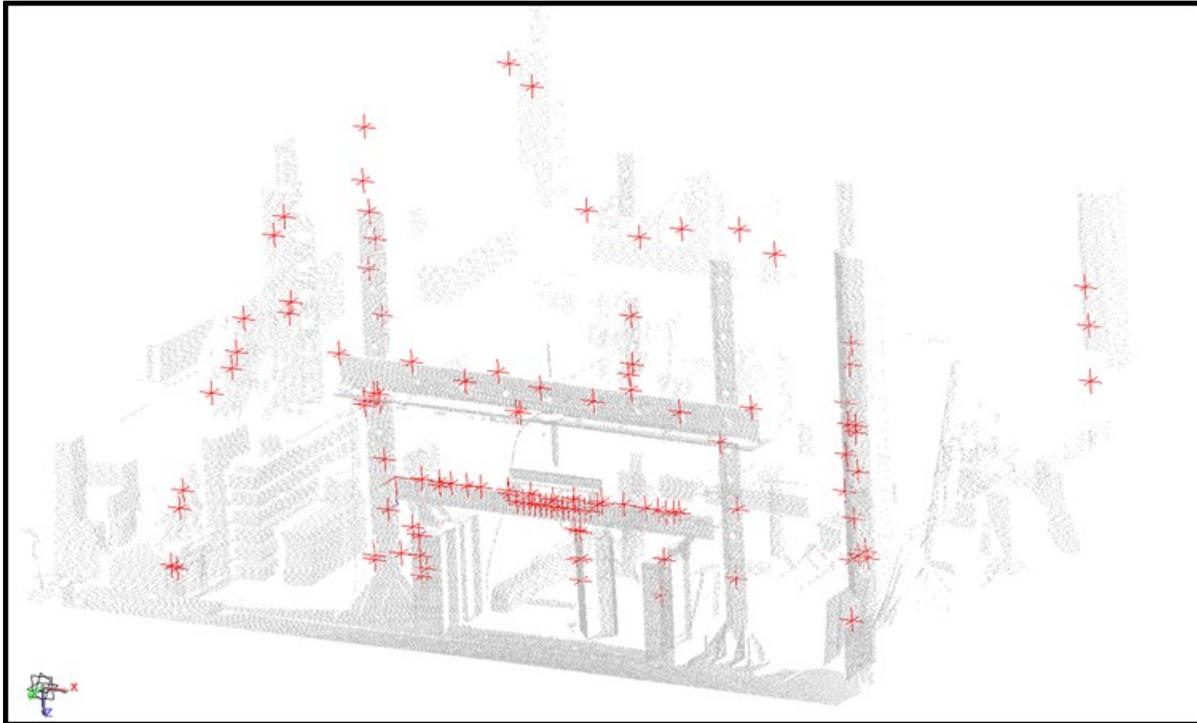


Figure 2: Measurement points for the Laser Tracker and the VMS AICON DPA

The two instrumentation to test were:

- the TLS Focus 3d from FARO Technologies, Inc. A light and versatile scanner that is well suited to fast and accurate measurements. It's a compact scanner characterized by an operative range that varies between 0.6 m and 120 m with a ranging error of ± 2 mm for scanner-object distances comprised between 10 m and 25 m. The processing of the scans was performed with the JRC software Reconstructor Software v. 3.1.0, of Gexcel Ltd that enables the carrying out of all the processing operations of the point cloud until the 3D model of the structure or building scanned is obtained;
- the low-cost digital camera Canon PowerShot S110, with a 1/1.7 " format sensor and a resolution of 12.1 Mpixel; 5x Zoom: 5.2 (g)-26.0 (t) mm (in terms equivalent to a film of 35 mm: 24 (g)-120 (t) mm) and Exif 2.3 (JPEG), RAW (CR2 Canon original) data format. The images processing was performed with the software Photoscan from Agisoft which implements the SFM. This approach is most suited to sets of images with a high degree of overlap that capture full three-dimensional structure of the scene viewed from a wide array of positions, or as the name suggests, images derived from a moving sensor [4]. The package was installed on an HP Z420 Workstation, with 64 GB of RAM and Intel Xeon processor CPU E5-16200 3.60 GHz, Nvidia Quadro K2000 video card.

At each load condition a set of measurements were taken with each equipment according to the **Error! Reference source not found.**

Load (kN)	DT	LT	DPA	TLS	CRP
0	√	√	√	√	√
11	√	√	√	√	√
26	√	√	√	√	√
40	√	√	√	√	√
54	√	√	√	√	√
68	√	√	√	√	

Table 1 Plan of the performed measurements

3. MEASUREMENT POINTS FOR METROLOGICAL EQUIPMENT

The Laser tracker was used with a twofold purpose:

- set up a reference frame with a vertical axis that can be adopted by the other measuring techniques;
- ensure the measurement of the deformation on the beam for a reasonable number of points.

The first task was realized using 6 special targets (hereinafter referred to as FT #), in aluminum but treated with reflective paint, realized in the workshop of the INAF-OAC for the group's Metrological research activities (Figure 3)



Figure 3: Target FT#

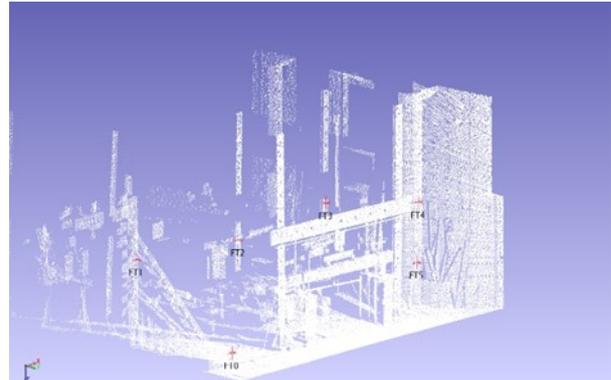


Figure 4: FT# position

These are targets whose center can be measured either with the LT, or with the AICON photogrammetric system. The six targets were fixed permanently in the laboratory area not

subject to loads and measured 3 times during the measurement leading to a mean error of $\sigma_{x,y,z}=0.15$ mm. The Figure 4 shows the distribution of FT# targets in the test area. The second task was made by constructing special holders for the LT reflectors to be drowned in the concrete to ensure their stability during all loading and unloading operations. The Figure 5 shows the special holders in different manufacturing steps.



Figure 5: Special holder for the LT reflectors in different manufacturing steps

The points, altogether five, were inserted on the beam at a height higher than the position of the neutral axis (in order not to trigger fractures in the load phase), at the supports of the beam, of the center line and to 1/3 and 2/3 of the length of the beam. The LT was always put in the station with its tripod, suitably heavy to ensure the stability of the instrument during the whole phase of measurements, remotely controlled with the software Spatial Analyzer (SA).

The AICON DPA metrological system included an inner reference system consisting of a cross and two calibrated bars and a set of coded and uncoded magnetic reflective targets. In the measuring phase, the camera settings were adjusted so that the reflective targets appeared sharply on a very dark background. The scene included the beam, the load frame and surroundings not affected by the load. All over the test area we put 119 measurements points including coded and uncoded targets (Figure 6), 33 of them were on the beam.

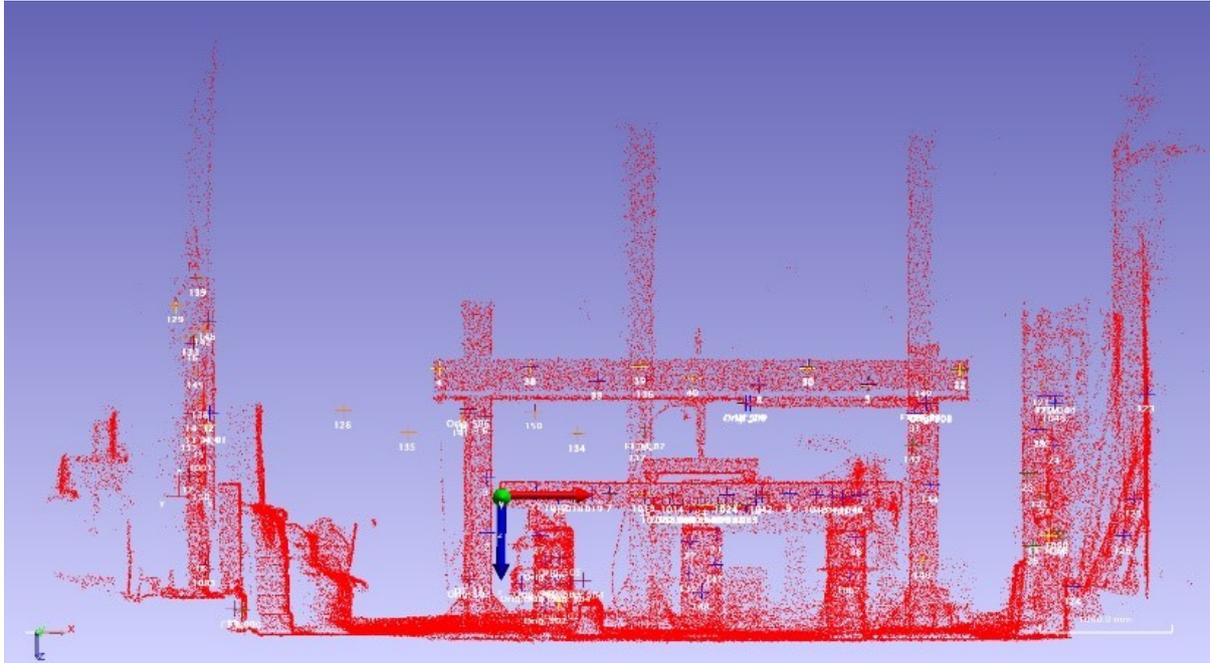


Figure 6: Distribution of AICON measuring points

4. PROCESSING STRATEGY

The processing strategy went on in parallel for CRP and TLS until the production of point clouds at different density. Then we treat them the same way following the scheme of Figure 7. The software for the treatment of images used was Photoscan by Agisoft. The software implements the SfM - Structure from Motion algorithm, a low-cost photogrammetric approach for high resolution topographic reconstruction. The SfM operates under the same basic theory as stereoscopic photogrammetry, however, it differs fundamentally from it, in that the geometry of the scene, camera positions and orientation are solved automatically without points that have known 3d positions. Indeed, these are solved using a highly redundant, iterative bundle adjustment procedure, based on a database of features automatically extracted from a set of multiple images with a high degree of overlap.

The Photoscan workflow consists in the following main steps: Data import, image alignment, generation of the sparse point cloud, optimization of image alignment, and dense image matching. For each processing phase Photoscan software proposed, to the user, various parameters affecting the accuracy and processing time of the final product. The quality of the dense point cloud can be set according to 5 different parameters to which 5 different resolutions correspond. These are parameters that create images at lower resolutions that allow a faster processing time to the detriment of the cloud resolution. Following the different parameters are enlisted:

- UltraHigh: the software works with the photos of the original size;
- High: causes image downscaling by factor of 4 (2 times by each side);
- Medium: source files are downscaled by factor of 16;
- Low: means further downscaling by 32 times more;
- Lowest: means further downscaling by 4 times more than Low accuracy.

On TLS dense point clouds are directly acquired during the survey. We set the instrument to scan at a resolution corresponding to a grid step of 1 mm and proceeded via software to a sub-sampling of 2 mm, 4 mm, 8 mm. Hereafter the processing strategy was the same for both CRP and TLS techniques.

CRP and TLS provide point clouds in which it is difficult to follow specific points, unless they have been conveniently targeted. In order to assess the deformation status, we then compared point clouds acquired at different loads and estimate differences. Commercial software usually makes point clouds to mesh (pointcloud2mesh), or mesh to mesh (mesh2mesh) comparison. Moreover, to exploit the enormous amount of points acquired and reduce the random noise, cloud points may be interpolated to fit surfaces or curves that are consistent with the deformation pattern or a known shape. This technique has been tested several times [6, 7, 8]. Furthermore, the edge of the beam had asperities that increased the measurement noise. The meshes produced at each load suffered from these asperities. Is clear that modelling the contour cancels out the phenomenon leading to a result dependent more on the beam behavior and on the experimental load, then on the roughness of the edges. Unfortunately, not many software includes this kind of modelling, or if they do it, usually the fitting is restricted to planes or spheres. So we performed mesh2mesh comparison inside the JRC Reconstructor software, while the fitting was obtained exporting cloud points in Matlab and performing there the processing.

In order to compare different point clouds, they must share the same reference frame. The TLS uses his own reference system, which is vertical and can be adopted if the instrument stays still undisturbed during the entire measurement process.

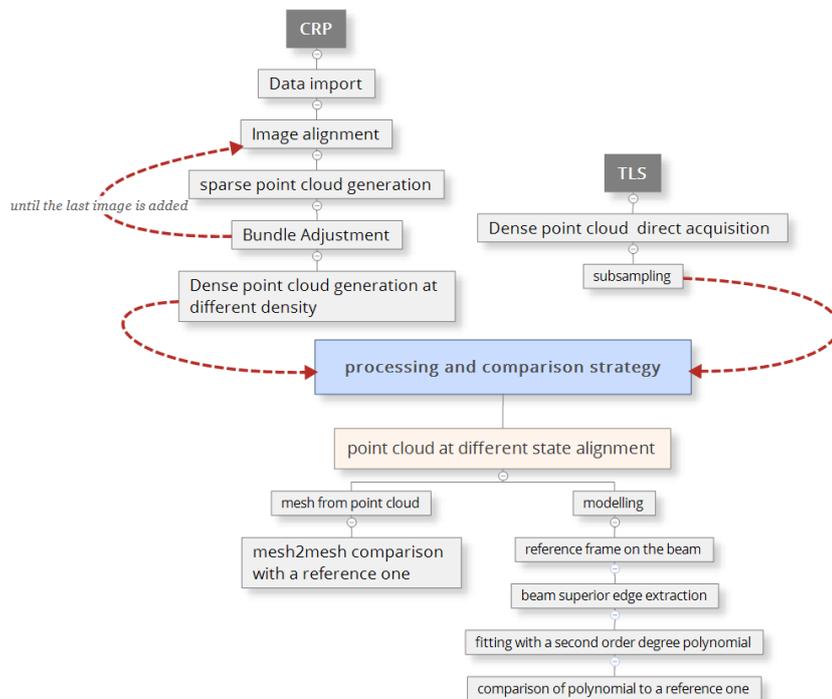


Figure 7: Processing strategy for CRP and TLS

Otherwise the following procedure could be adopted:

- Extraction, from point clouds, of portions relative to test areas not subject to movement;
- co-registering of all these portions with respect to one fixed as reference;
- application of the rotation matrix to the whole scene.

Point clouds generated by photogrammetric measurements instead come with an arbitrary reference frame and an arbitrary scale of the model. We used, as control points, the same 6 points used to fix the reference frame for the DPA measurements which provided both reference frame and model scale. When acquiring images for 3d models, control points are measured with a total station or GNSS instrumentation, so the scale of the model, which is crucial when assessing deformations, is affected by an uncertainty depending on the precision of the topographic survey, which is certainly lower than that obtained in our experiment. To reduce the error on scale factor two or more calibrated bars can be used on the field, improving the reference frame fixing using the same strategy we suggested for TLS scans.

As already said, on point clouds two kind of processing were investigated:

- mesh2mesh comparison;
- modelling of the profile of the beam at each load with second order polynomials and comparison of the curve.

Since the front face of the beam was close to a regular rectangle, we extract the superior edge of the longitudinal section. To reduce each dataset in two dimensions, we built a reference system on the beam with the following constraints:

- origin contained in the left end of the beam;
- Z axis vertical and pointing down;
- X axis lying on the front face of the beam;
- Y axis as to form a right-handed system

The displacements were computed comparing the z coordinate of each load with the z of the reference point cloud. We then assessed the accuracy of the methodologies comparing the TLS and CRP displacements with those estimated by the DPA at the 33 targets on the beam (Figure 8) and computed the global RMSE.

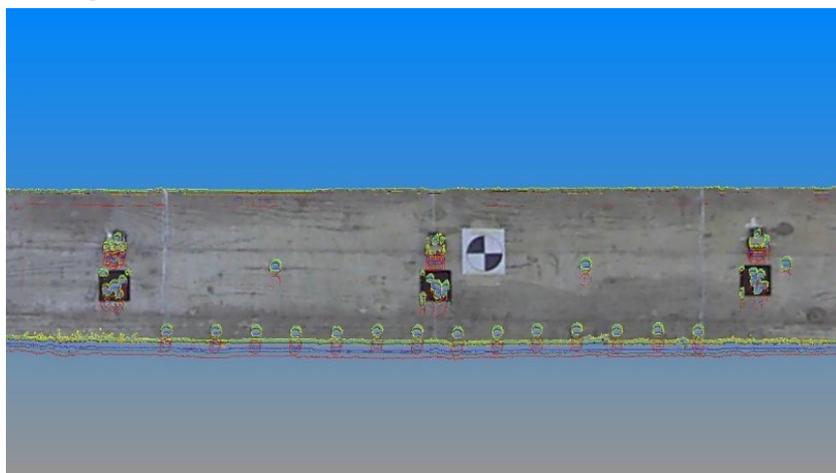


Figure 8: Point cloud with contour for each load

5. PROCESSING AND RESULTS

With the CRP methodology and for each load condition, with the exception of the load 68 kN, the photogrammetric images were taken with the Canon PowerShot S110 digital camera and processed with the Photoscan software.

The point clouds were georeferenced through the FT# points, in this way the z axis was vertical. The Table 2 shows the RMS on GCPs (FT#).

Load (kN)	RMS X (mm)	RMS Y (mm)	RMS Z (mm)
0	1.01	1.36	0.71
11	2.62	1.34	0.69
26	0.64	0.83	0.68
40	0.70	0.60	0.33
54	3.25	5.03	2.27

Table 2: RMS on the GCPs

All CPR surveys were processed in Ultra High mode with very high CPU time consuming. Table 3 shows the data and the processing parameters for each load.

Load (kN)	n. images	Parameters dense point cloud	Processing time
0	98	Ultra High	2 h 10'
11	112	Ultra High	3 h 40'
26	114	Ultra High	4 h 30'
40	108	Ultra High	4 h
54	105	Ultra High	3 h 15'

Table 3: Data and processing parameters of CRP surveys

As stated before, in order to obtain displacements, we followed the processing strategy described in the (Figure 7).

The Table 4 reports the comparison between the displacement measured using the DPA and the CRP mesh2mesh methodology.

Load (kN)	RMS (mm)
11	2.71
26	2.16
40	2.42
54	1.43
Global RMS	2.18

Table 4: RMS from mesh2mesh comparing strategy

The Table 5 shows the comparison between the displacement measured using the DPA and the CRP modelling processing strategy.

Load (kN)	RMS (mm)
11	1.42
26	1.5
40	1.69
54	0,78
Global RMS	1.35

Table 5: RMS from modelling comparing strategy

The improvement in global RMS, when modelling, is about 40%.

A second part of the CRP trial concerned the study of the variation of the accuracy as a function of density of the point cloud, and consequently also with the processing times. We then proceeded to process loads 26 kN and 54 kN even with the densities provided by Photoscan: High, Medium, Low, Lowest. The processing times for the generation of clouds were various, so it is of interest to evaluate whether it is necessary to produce a dense cloud (Ultrahigh) or if we can reduce point cloud density. Ultrahigh processing data is again included in the tables for easier reading of the results.

Table 6 shows surveying data and processing parameters.

Load (kN)	n. images	density	Processing time	n. points
26	114	Ultra High	4 h 30'	14,391,686
26	114	High	1 h 26'	4,238,977
26	114	Medium	47'	1,103,430
26	114	Low	6'	260,027
26	114	Lowest	3'	17,441
54	105	Ultra High	3 h 15'	12,577,541
54	105	High	55'	3,819,184
54	105	Medium	13'	999,958
54	105	Low	3'	237,734
54	105	Lowest	2'	16,876

Table 6: CRP Parameter and data processing

Table 7 shows in detail the results of the comparison with the displacement measured using the DPA and the CRP modelling methodology at different point cloud density.

	26 kN RMS (mm)	54 kN RMS (mm)	Mean RMS (mm)
Ultrahigh	1.50	0.78	1.35
High	4.42	1.35	2.88
Medium	5.62	4.51	5.06
Low	4.06	17.32	10.69
Lowest	23.08	15.28	19.18

Table 7: RMS for different densities

RMS values are strongly variable at different point cloud density (see Low Density). As results shows, to achieve reliable values comparable with metrological accuracy we needed to use Ultrahigh density for all CPR processing.

In the Figure 9 and Figure 10 are the diagrams of the processing time versus the number of points of the point clouds. Figure 11 shows the behavior of the Global RMS versus the number cloud points.

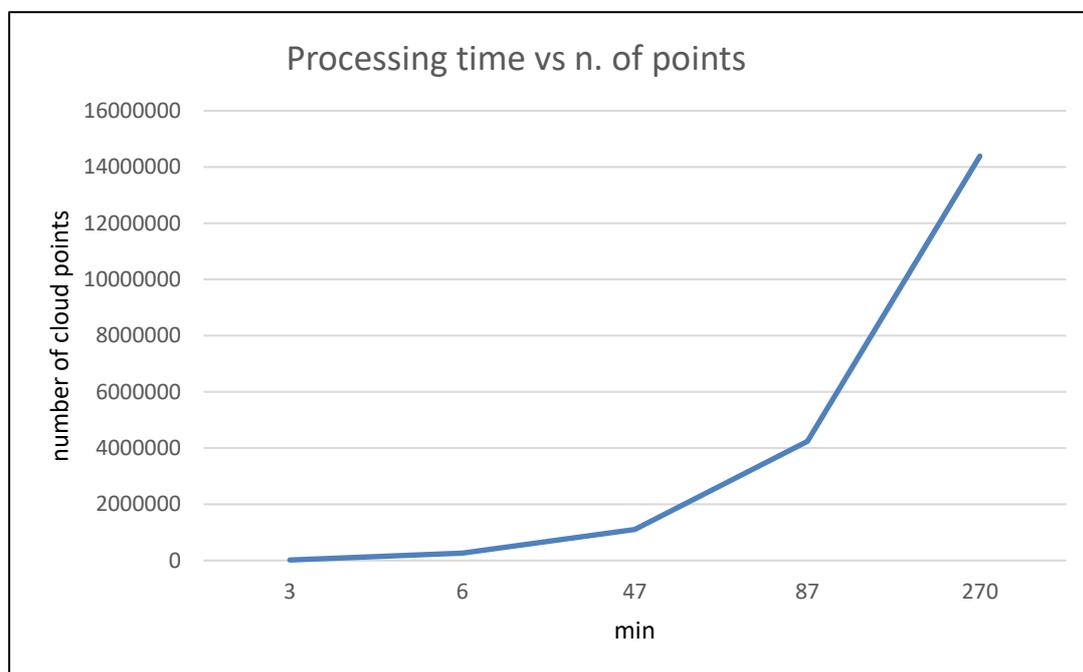


Figure 9: Chart load 26 kN

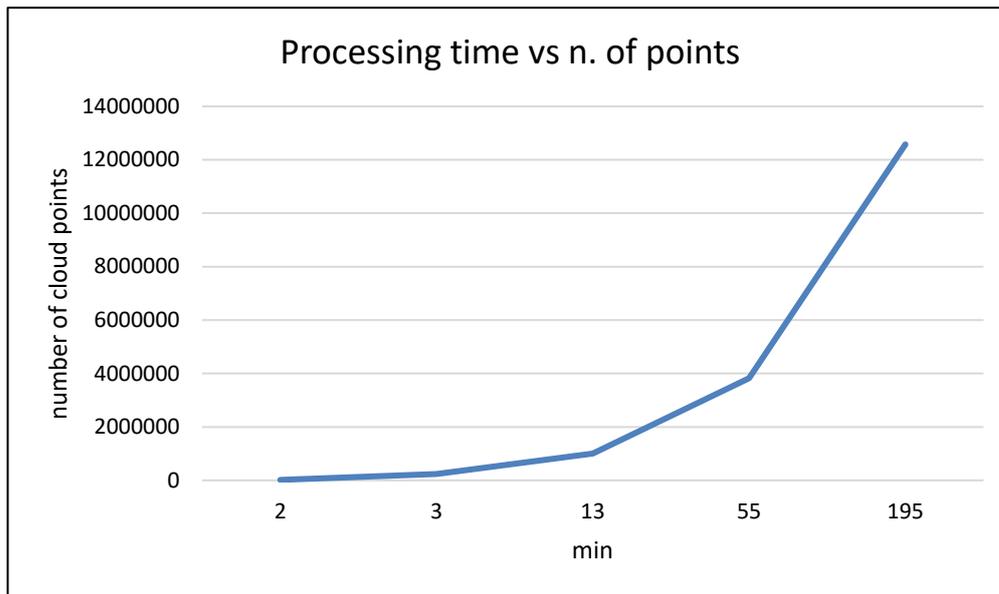


Figure 10: Chart load 54 kN

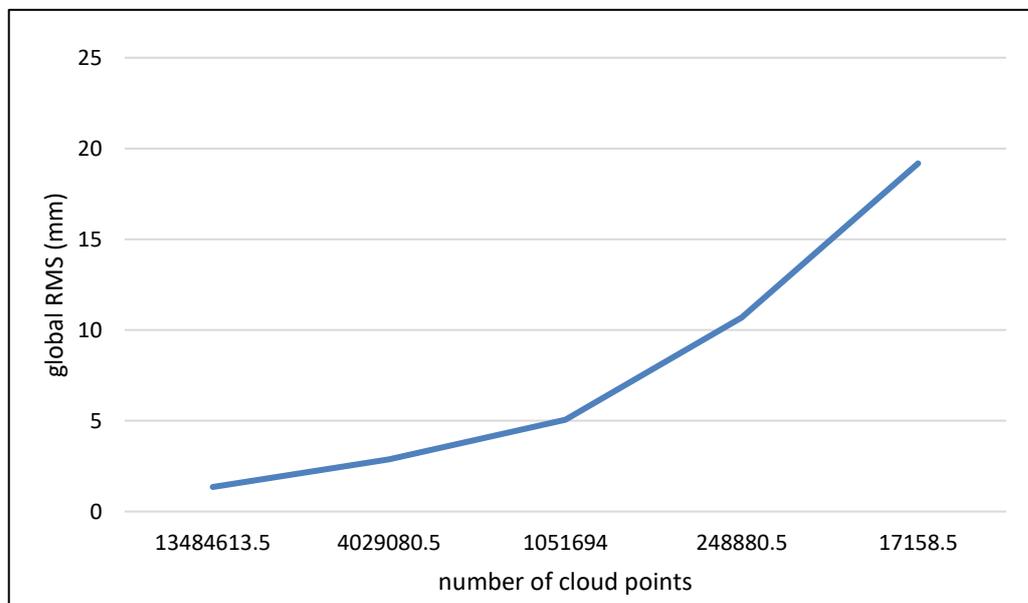


Figure 11 Global RMS vs number of cloud points

Also, for the TLS we followed the workflow describe in the Processing strategy (Figure 7). The Table 8 reports the comparison between the displacement measured using the DPA and the TLS mesh2mesh methodology at different sub-sampling at load 26 kN and 54 kN.

Load (kN)	Sub 1 (mm)	Sub 2 (mm)	Sub 4 (mm)	Sub 8 (mm)
11	1.01			
26	0.98	1.18	2.03	2.66
40	0.97			
54	0.99	1.27	2.06	2.99
68	0.92			
Rms Glob	0.96	1.23	2.05	2.83

Table 8: Results for the TLS mesh2mesh at the different sub-sampling

Table 9 shows the comparison between the displacement measured using the DPA methodology and TLS modelling at the different sub sampling.

Load (kN)	Sub 1 (mm)	Sub 2 (mm)	Sub 4 (mm)	Sub 8 (mm)
11	0.38	0.56	0.72	0.58
26	0.42	0.74	1.16	1.16
40	0.6	0.92	1.2	1.64
54	0.63	0.88	1.18	1.28
68	0.62	0.63	0.66	0.8
Rms Glob	0.53	0.75	0.98	1.2

Table 9: Results for the TLS modelling at the different sub-sampling

In the Figure 12 the trend of the global RMS at the different point cloud resolution (1, 2, 4, 8 mm) are shown.

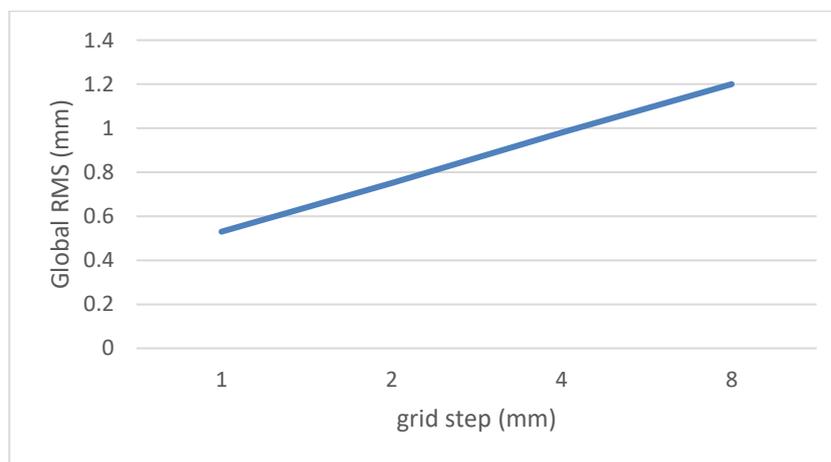


Figure 12: Global RMS vs TLS grid step in mm

6. CONCLUSIONS

The comparisons performed between the different techniques highlighted the limits and potentialities of the two geomatic techniques used. We shown that modelling the behavior of the beam leads to significantly better results than using the mesh2mesh comparison. For the CRP the increase in accuracy was in the order of 40 %, while for the TLS of 50%.

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Regarding CRP methodology, we stated that decreasing the density of the point cloud does not bring great advantages except for the time of processing at the expense, however, of the accuracy in the assessment of the deformation. It will be interesting to check if this happens with ultimate low-cost digital cameras more performing compared to the PowerShot 110 used in this experimentation.

With TLS we experienced a linear trend between the global RMS and grid step. Even grid steps of 2, 4 and 8 mm, RMS were always compatible with the accuracy needed for displacements assessment leading to time saving during surveys and computer with less performances during processing. As a drawback modelling needs specific routines not usually implemented in commercial software.

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