COMPARISON OF TERRESTRIAL LASER SCANNERS IN PRODUCTION OF DEMS FOR CETARA TOWER

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ABSTRACT

The main goal of this work is to study and experiment the use of the terrestrial laser scanning technique in order to survey an architectural heritage; we try to estimate both the precision and the accuracy of the results, and to supply a methodology for the treatment of the acquired data. The experiment concerns the survey and the modeling of a tower characterized by a very articulated plan and a complex geometry placed in Cetara (Amalfitan Coast). We use five different laser scanning instruments, both at medium and long range. In order to estimate the laser sensor performances with respect to two main parameters, the range and the accuracy, we carried out a number of scanning at both different distances from the object and various resolutions. The surveys carried out with the different instruments demanded different design, planning and tests execution. Modeling has been carried out using several commercial software used to filter the scan results and to reconstruct both the nurbs which are part of the 3D model and the solid one by means of triangulation. In any phase of the work we try to compare a number of characteristics of the five laser sensors we used in order to define their performance and above all their suitability for surveying an architectural heritage such that we choose as Test. Before making the comparison, we aligned all data in order to transform them from the local reference systems to a common one.

1. INTRODUCTION

One of the main features of the laser scanning technique is to collect a great data amount without interacting with the sample and to give a detailed 3D model of the measured object. The main goal of this work is to study and experiment the use of the terrestrial laser scanning technique in order to survey an architectural heritage; we try to estimate both the precision and the accuracy of the results, and to supply a methodology for the treatment of the acquired data. A number of tests has been carried out by means of five different laser scanning instruments on a very articulate and geometry complex tower placed in Cetara (SA), in Amalfitan Coast.

The Tower is constituted by a main body with a roughly square plan articulated in seven levels. Three floors are underground, one floor is at the level of the main road and the others three over that. Each floor is different by the others. There are also a bastion with a circular plan connected to the main body and a turret joined to the Tower by means of a drawbridge.

The surveys carried out with the five different instruments demanded different design, planning and execution. In order to carry out the survey of the Tower it has been necessary to run an high number of scans from various points of view and with different resolutions. The second phase of the work, namely editing and modeling, has been carried out using several softwares in order to filter the nurbs, to align them and to produce – by meshing - the 3D model. Afterwards, we globally aligned all the nurbs obtained by any laser scanning instruments, in order to transform all the data in a single reference system and to make possible to compare each one with the others.

In this paper we talk about the data acquisition on site, the data processing and finally their analysis and comparison.

2. RAW DATA ACQUISITION

In this work we compared the surveys carried out on the Tower of Cetara by means of five different ground-based laser scanning instruments:

- Callidus CP3200 by Trimble
- Cyrax HDS2500 by Leica Geosystems
- Mensi GS200 by Mensi Inc.
- Optech ILRIS-3D by Optech Inc.
- Riegl LMS Z420i by Riegl

We show in table 1 a number of technical characteristics of the laser scanners we used.

	CALLIDUS	CYRAX	MENSI	OPTECH	RIEGL
Laser Class	1	2	2	1	1
Measure Technology	Time of Flight	Time of Flight	Time of Flight	Time of Flight	Time of Flight
Dim (cm) (LxWxH)	46x30 (LxΦ)	40x34x43	34x27x42	31x31x21	46x21 (LxΦ)
Weight	17.1 Kg	20.5 Kg	13.6 Kg	12 Kg	14.5 Kg
Vertical field of view	40÷180°	40°	60°	40°*	80°
Horizontal field of view	0÷360°	40°	360°	40°*	360°
min range(m)	-	1.5	1	3	2
max range(m)	40÷80**	100	200÷700	> 1500	> 800
Angular Accuracy	0.009°	0,0034°	-	0.0045 °	0.002° V 0.0025°H

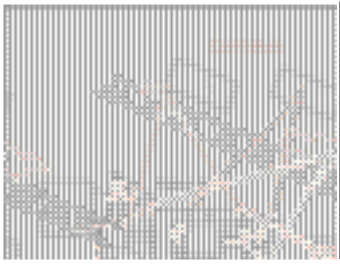
Table 1. Laser scanners specifications

The figure 2 shows the Tower's plan at the ground level (ground floor) with the scheme of the location of the scanning stations used for each survey and some information concerning the surveying modalities. In any case, in accordance with the laser range, the survey has been planned so that to limit as much as possible the hidden areas. Although the technical characteristics of all the instruments we use are suitable for architectonical survey, therefore the so different values of

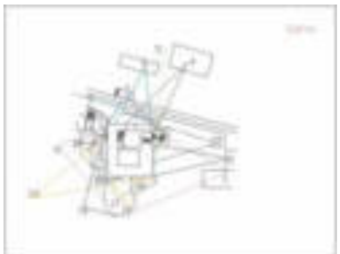
* 360° with optional accessories

** depending on surface

ranges (maximum range is variable between 40 to 1500m) have strongly influenced the possibility to carry out the whole survey of the Tower.
In the case of Callidus instruments, we have not been really able to stand on the pier because of the distance between it and the Tower was nearly 200m. As a consequence, the sea-side façade of the Tower, was not surveyed. Also the lower part of the beach-side façade of the Tower was not surveyed because it was covered by a scaffoldings at the time of the survey. The high part of that façade has been so acquired from the main road and from the balcony of the surrounding villas.
For Cyrax instruments we could not complete the Tower's survey too. Because of the low range of the instrument, a wide area is lacking of data; such area corresponds to the circular bastion that faces to the sea.
Other important instrumental features which strongly influence the number of nurbs which are necessary in order to survey the whole object are the presence of the power and the width of the field of view. Since four of the five instruments we used were power-driven, just a number between six and fourteen nurbs carried out from six to eight stations have been used in order to make a "complete" survey of the Tower. Only for Cyrax one, the lack of motorization together with the small field of view (40° both in vertical and in horizontal direction) caused the need to carry out fifty-six scansions from eighteen different stations.
For the scanning step on the object, when it was possible we set an average values of 5mm for Cyrax and Mensi, 7mm for Optech and 10mm for Callidus and Riegl; just for a few overall or farther scansions, the set step was greater (up to 50mm).
Finally, looking at the information in figures 2, you can note that a low resolution integrated digital camera is nearly always present. Just in the case of Riegl, the instruments is supplied with a support that allows to connect an external photogrammetric camera. We used a Nikon D100 with a calibrated lens, in order to carry out some photograms having an high resolution level and controlled metrical characteristics. About Callidus e Cyrax, beyond the images acquired by the integrated low resolution camera, we also acquired some highest resolution images with Nikon camera too.
After surveying on field, data processing follows; the first phase consists in editing the nurbs to the aim to remove from the clouds of points those points which don't belong to the object, as branches and leaves, pylons, etc. *Registration* is used in order to align the single scansions in order to have a single reference system while the *Merging* for the generation of meshes. Starting from the model is then possible to elaborate many other products like sections, profiles and orthophoto.
All the surveys have been processed with the PolyWorks software ver.9.1, even if some elaboration steps have been also performed by means of other software relises.
On details:
- As concerns the Callidus, for data acquisition we used the Laser Measuring System ver. 1.1.0.37 software while the 3D-Extractor was used for editing and aligning the nurbs; the 3D-Reconstructor ver.1.9.8 was instead used in order to make a complete elaboration, including editing, pre-processing, registration by homologous shapes, mesh, texture mapping and orthophoto.
- With regard to Cyrax's data, we used Cyclone ver.4.1 for both the data acquisition and the editing, filtering, registration and mesh phases. The registration has been done using two different methods that are "overlapping of corresponding points" and "topographical" one.
- Mensi data have been completely processed with the Realworks software ver.4.2.
- With regard to Riegl data we used RiscanPro ver.1.1.1sp11 only for the acquisition and registration of the nurbs and the 3D Reconstructor software for all processing steps, exept for making orthophoto.
However, using Polyworks we carried out the whole processing work starting from the data acquired from the five instruments; we talk about the elaboration results and the comparisons between the instruments in the following paragraphs.

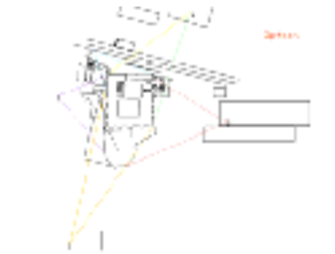


	CALLIDUS CP 3200
# scanning	8 from 8 stations
scanning step	10 mm (5 ÷ 50 mm according to distance)
photograms	Integrated



	CYRAX HDS 2500
# scanning	56 from 18 stations
scanning step	5 mm (10mm from station n. 13)
photograms	Integrated

	MENSI GS 200
# scanning	7 from 5 stations
scanning step	5 mm (10 mm from station n.1)
photograms	Integrated



	OPTECH ILRIS-3D
# scanning	6 from 6 stations
scanning step	7 mm (33 mm from station n.1)
photograms	Integrated

	RIEGL LMS Z420I
# scanning	14 from 6 stations
scanning step	10 mm (5 ÷ 50 mm according to distance)
photograms	External

Figure 2. Planned location of the scanning stations

3. EDITING OF NURBS

The nurbs acquired from the five laser scanning instruments, even if they are not characterized from the same resolution (for operating reasons), have been edited and compared.
Figure 3 shows the point clouds acquired with a single scan on the façade towards the road by means of the five instruments, once edited and at several zoom levels (figure 4).
Looking at the nurbs shown in the figures, it is possible to make

some remarks on the structure and distribution of the data sets.
In details, all the data acquired from the different laser scanners, with except for Mensi, can be defined "raw" because no average has been made on them and, as a consequence, no information has been lost. It has not been possible, as we said, to obtain the raw data by using the laser scanner Mensi since this instrument only outputs an average value among the different scansions we do in order to make the survey.
A second remark regards the data thickness which is different for any instrument. The nurbs acquired with Callidus are less thick, because they have been acquired with a scanning step of 10mm. As a consequence, only the data obtained with the other laser scanners are comparable since they were acquired with a common scanning step of 5mmm; they look on the whole be similar. In figure 4 the points belonging to Callidus nurbs have been magnified three times in order to allow a better visualization. Even if the thickness of the points belonging to the nurbs acquired from the four instruments is comparable, the survey of the architectonical details of the surface is meaningfully different in any case. In details, you can notice that the level of detail is optimal as concerns the Mensi data, very good for the Cyrax and Optech data and medium for Riegl data. The Callidus data are not considered in this comparison because, like we said, the scanning step we set up on the façade is double then the others.

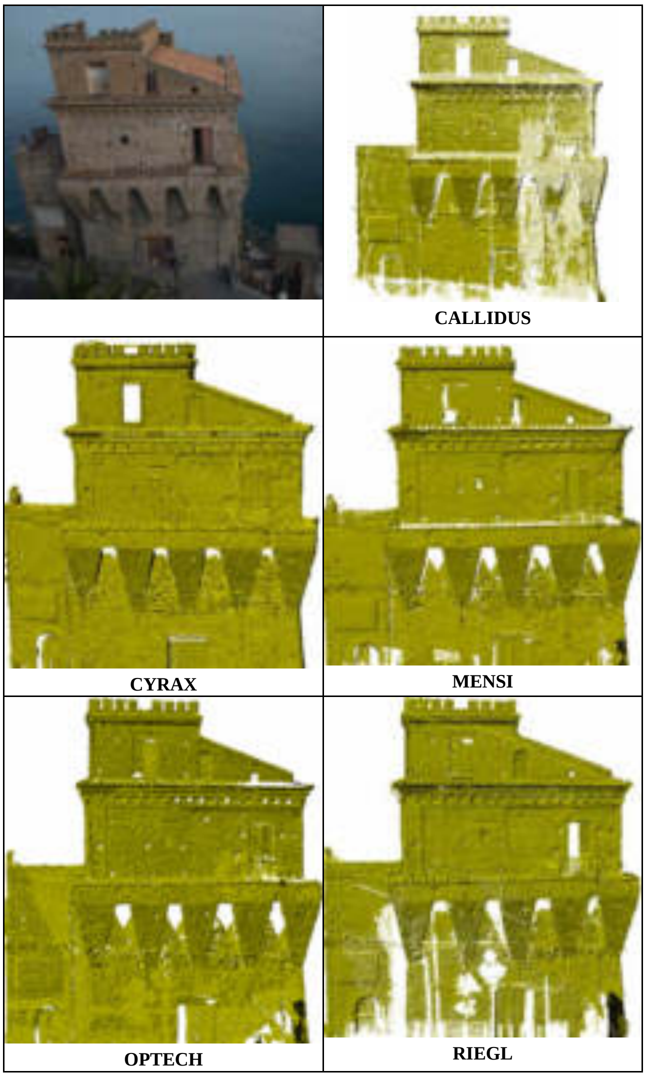


Figure 3. The road side façade nurbs

About the typology of data, we can say that the short range lasers, except for Callidus, are able to produce very detailed data, while the data acquired from the long range ones, except for Optech, are less detailed. Although the data from Riegl are the noisiest, the very high speed of acquisition together with the great range, make this an optimal instrument.
Moreover, the holes caused by lack of data, which are present especially on the sea- and terrace-side façades, in the façade shown in figure are not very present since it is easily accessible from the road located at med level as regards it; as a consequence the laser beam is not strongly tilted in the vertical direction and because of that there are not hidden areas.
This phase of work, namely *Editing* has been analogous for all the data acquired with the five instruments; the only difficulties we met are due to the closeness to the Tower of some objects as pylons and more then ever to the vegetation which partially covers the masonry.

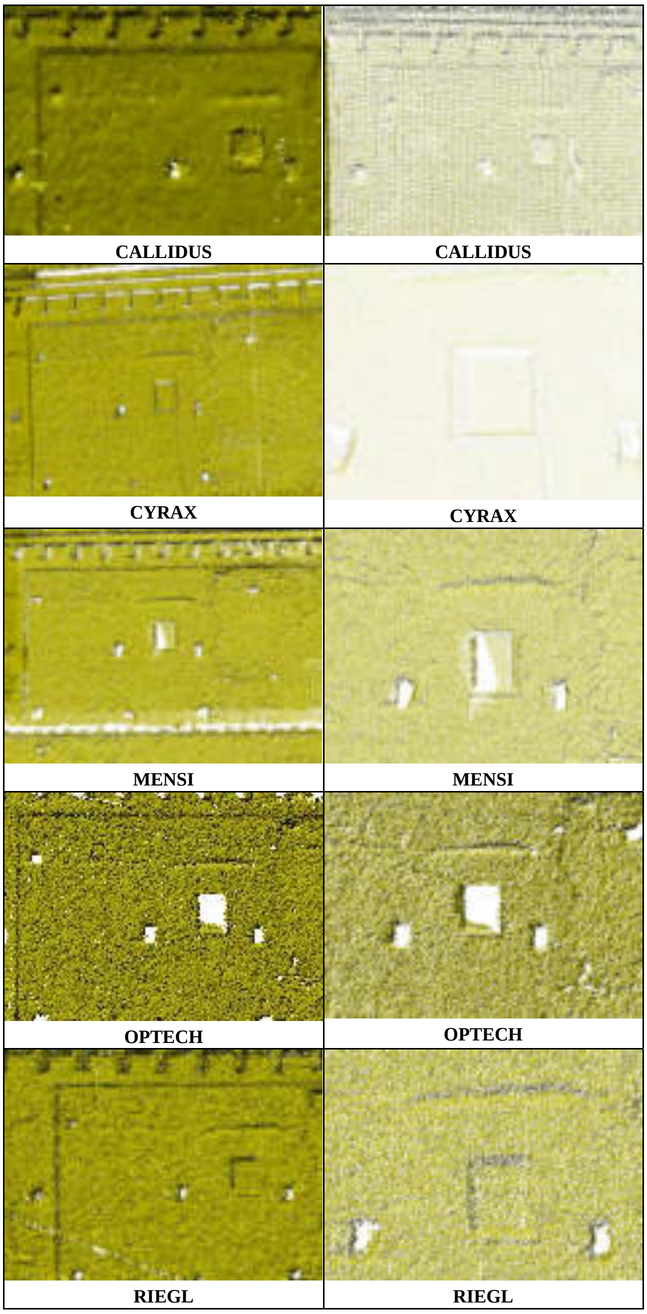


Figure 4. Details of figure 3

4. REGISTRATION

Once the single nurb was edited, we aligned all the nurbs in order to obtain a single nurb in the coordinate system of the reference scansion. Such operation, which is said *Registration*, consists in a roto-translation at six parameters of the points coordinates acquired in any station in the intrinsic reference system of the sensor in order to transform them into an absolute reference system coinciding with that of the first station.
You can use two different way for registering of two nurbs: "overlapping of common points" and "topographical method".
In the last case it is necessary to preventively carry out a support topographical survey of the object; the acquired points therefore will be subsequently use for the registration. Using the Polyworks software we aligned the nurbs by means of the method of overlapping of common points, to the aim to create for each instrument a sole point cloud model. In details, as far as Cyrax data, the geo-referencing carried out by means of the Cyclone software with the topographical method has been holded. In table 5 we show the result of the image alignment process on each models, made up by the four façades and the roof; the process is an iterative one which converges when all incremental transformation matrices computed during one iteration are identity matrices.

	Convergence (m)	Mean (m)	St. Dev. (m)
CALLIDUS	2.9e-11	-4.7e-5	1.0e-2
CYRAX	9.7e-11	-9.6e-5	7.9e-3
MENSI	9e-4	2.4e-2	8.5e-3
OPTECH	1.3e-5	-5.5-4	1.2e-2
RIEGL	1.4e-7	-7.7e-5	1.3e-2

Table 5. Report on nurbs alignment

You can notice that the convergence value is very small for the two low-range laser scanners, Callidus and Mensi; this is index of an excellent alignment. The worst result about the convergence is that one obtained with Mensi data, while both the two long-range scanners, Optech and Riegl are characterized by intermediate values of convergence. The averages of the alignment residual are all of the same order of magnitude, except for Mensi whose value is significantly higher then others; this value confirms that the nurbs are not aligned in the right way. The standard deviation values are instead of the same orderfor all the instruments, namely 1cm, uncorrelated from the scanner typology (long or low range).
Figures 7 shows the result obtained for the alignment of the various nurbs, divided for façade. Looking at the images shown in the figure, we can make some remarks. First of all, you can notice that the range of the instrument influences remarkably the result; as a matter of fact, if on one hand the short-range laser scanners are characterized by higher precision, and therefore they are particularly suitable for surveying architectonic heritage, on the other hand the long- range makes possible "more complete" surveys. For example, if you look at the beach-side façade coming from Callidus data, you notice that it is not complete because the low side of the Tower was covered by a scaffolding at that time, then it was not interesting to survey it, while the high side was too far for the instrument range. In the figure you can see the part of the façade which has been surveyed from a home terrace placed opposite of the beach. For the other side too, the low range of the laser scanner made a whole survey impossible. Moreover, in almost all the images shown in figure, some smaller or larger areas coloured in blue are present; they are representative of holes of data in the nurbs due to both the presence of some part of the Tower which are jutting out the façade or some object as road signs, pylons, etc. placed in the middle between the laser and the Tower; all these caused hidden areas. On the end, as far as the Terrace-side survey is concerned, since we could reach the terrace of the villa opposite the Tower, we were always able to survey also the circular bastion of the Tower, which is far-away on the left side of the façade. Nevertheless you can notice the presence of big holes above all in Riegl and Mensi data.

5. GLOBAL ALIGNMENT OF NURBS

In order to compare the five surveys, all data have been transformed into a single reference system. In details, we aligned the four façades from Callidus, Mensi, Optech and Riegl regarding that from Cyrax, which was the only one having an "absolute" reference system. Indeed, the reference system used in order to align and register any scan, is generally a local Cartesian orthogonal system with the origin in the first station point, X axis nearly parallel to the façades, Y axis with direction entering towards the façade and Z turned towards the high. For Cyrax data, the reference system was instead the same used in order to register the nurbs by means of topographical method; this one was the system used in order to align all together the five surveys, separately for any façade.
The image alignment technique we used is based on an iterative algorithm that computes an optimal alignment by minimizing the 3D distances between surface overlaps in a set of 3D image acquired from unknown viewpoints. Table 6 summarizes the image alignment process results about the convergence, the medium value and the standard deviation of the residuals. You can notice that the results we obtained in the alignment of the single nurbs regarding with Cyrax one are quite homogeneous while those coming from the alignment of the scansions belonging to the single model are much more varying (see Tab. 5). All the mean values and s.d. of the residuals are of the order of a millimeter, and the convergence is of a few micron; this last value, much bigger than the one we obtained for the single models, is a index of a shift among the various surfaces surveyed with the five different laser scanning instruments.

	Convergence(m)	Mean (m)	St. Dev. (m)
CALLIDUS	1.3e-8	-2.7e-5	1.3e-2
MENSI	2.1e-7	-9.1e-5	1.2e-2
RIEGL	4.5e-7	-5.3e-5	1.2e-2
OPTECH	1.5e-7	-2.1e-4	1.2e-2
SEA-SIDE			
CALLIDUS	-	-	-
MENSI	3.7e-7	1.8e-4	1.3e-2
RIEGL	0.1e-5	7.5e-5	1.2e-2
OPTECH	0.1 e-5	-1.3e-4	1.3e-2
BEACH-SIDE			
CALLIDUS	3.0e-6	-9.7e-5	9.4e-3
MENSI	9.0e-6	-3.9e-5	9.1e-3
RIEGL	3.0e-6	-3.4e-5	1.2e-3
OPTECH	8.0e-6	-2.3e-5	1.3e-3
ROAD-SIDE			
CALLIDUS	3.0e-8	0.6e-5	1.4e-2
MENSI	1.0e-6	7.7e-5	1.1e-2
RIEGL	2.0e-6	6.0e-6	1.2e-2
OPTECH	1.0e-6	5.5e-5	1.4e-2
TERRACE-SIDE			

Table 6. Report on nurbs alignment.

The points belonging to the model have been then interpolated on a grid with 1cm of step, using the kriging algorithm, which is implemented in the Surfer software ver.8.0 by Golden Software. Afterwards, ever for any façade, we put from the "global" nurb apart the single nurbs coming from the various instruments; in this way all the nurbs have holded a single reference system.

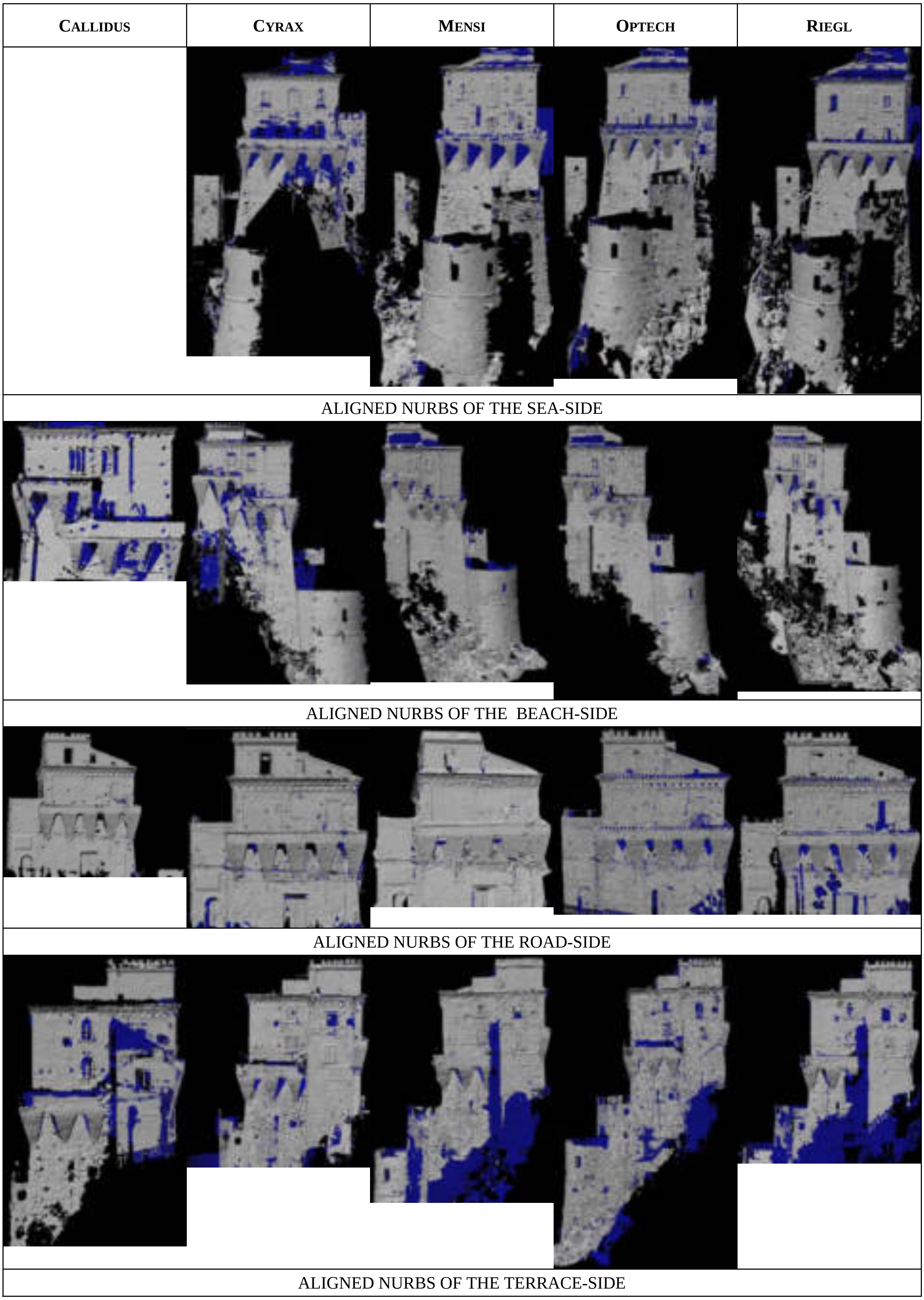


Figure 7. Aligned nurbs

In the end, we compute the residuals of the points belonging to the five nurbs in comparison with the gridded surface coming from Cyrax data. In details, we compute the vertical difference between the Z value in the data file and the interpolated Z value on the gridded surface. It gives a quantitative measure of how well the grid file agrees with the original data. We show in table 8 a statistical analysis (mean value and standard deviation in meters) of the computed residuals. Looking at the residual values on each façade, you can notice that: on the sea-façade the values are quite low, with an average of 2.5cm but with s.d. values very high, varying from 30cm to over a meter; on the beach-façade the residual are instead high, with medium values from 3 to 15 cm even if with s.d. much more low, of 3-7cm; the road-façade is the "best one", since the residual are of few millimetres for all the instruments, with s.d. of the order of 10cm; finally on the terrace-facade the residuals are on the average of 2cm, showing a behaviour as the sea-facade, with s.d. equally high, varying from 20 to 75cm.
On the other hand, if we compare the residuals of the single instruments, we see that the behaviours of Cyrax, Mensi and Riegl are similar. The residuals evaluated with respect to the grid are all of the same order of magnitude, of about 2cm. On the other side the behaviour of Callidus is similar to that of Optech, and the average of the residuals is about 5-6cm. For the five instruments, finally, the s.d. are comprised in the range from 30 to 50cm. We underline that global cloud that we have used to compute the residuals of the individual clouds is not taken like "truth", since is not the product of a survey carried out with a better known approach than the laser scanning we are testing (as it could be a photogrammetric technique): it must better be seen as an unique reference surface used to compare all measured data. The results summarized in the table and our comments do not want to give in any way an experimental information about the accuracy of the single instrument neither they want to compare them by using their accuracy as a parameter: they better try to stress that the result of the survey of an object by means of a laser scanning technique (in terms of the numerical model) can vary in a significant way when using different instruments. We eventually average arithmetically all the residual summarized in table, in order to obtain a values that summarizes the behaviour of the residuals, and we obtain a value of about 35cm for the average and of nearly 60cm for the s.d.

	Sea	**Beach**	**Road**	**Terrace**
Callidus	-	-0.148±0.661	-0.005±0.049	-0.024±0.268
Cyrax	0.014±0.364	-0.033±0.503	-0.004±0.263	-0.011±0.200
Mensi	-0.003±1.356	-0.027±0.404	-0.003±0.115	-0.048±0.743
Optech	-0.060±0.664	0.117±0.719	0.007±0.112	0.010±0.633
Riegl	0.025± 0.323	-0.049±0.516	-0.001±0.150	-0.002±0.517

Table 8. Mean and standard deviation of the residuals of the nurbs in respect to Cyrax grid (m)

6. CONCLUSION

On the operative characteristics of the laser scanners, in the common survey contexts, we can do some remarks:
- the choice of the laser scanning instrument must be related both with the dimensions of the object and with the wished accuracy level;
- the survey should be accurately planned with the aim to obtain a complete description of the object; more acquisitions from various stations may be necessary, above all in order to cover eventual gaps caused by the object shape;

On planning the survey geometry and the number of nurbs we try to reach a convenient equilibrium point between two opposite requirements. On the one hand we took into account that the size of data acquired with a laser survey catches up important dimensions quickly, with consequent fallen back on the abilities of the common processors, or at least on the processing times; on the other hand that the obtained accuracy once the raw data have been processed is strongly influenced from data redundancy. The comparison we made on both the nurbs or the models coming from the five laser scanning instruments demonstrates how much the use of instruments with a maximum range value suitable for the size and complexity of the surveyed object may be important. Indeed, if on one hand the medium-range instruments are often characterized by a better accuracy, on the other hand their use prevents for carry out the whole survey of some wide and complex objects. In the end, we underline the being of a quite large shift among the five set of surfaces made by point clouds; when one survey is compared with the others lasts a difference amounting in some tens of centimetres, even if all surveys had been transformed in a single reference system.

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