FAST AND ACCURATE CLOSE RANGE 3D MODELLING BY LASER SCANNING SYSTEM

Gabriele Fangi, Federica Fiori, Gianluca Gagliardini, Eva Savina Malinverni
University of Ancona, via Brecce Bianche, 60131 Ancona, Italy
tel. ++39-071-2204742, fax ++39-071-2204729
fangi@unian.it malinverni@unian.it
www.ing.unian.it/strutture/fimet/fangi

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ABSTRACT
Completeness, speed, accuracy are some aspects of the laser scanning system for the acquisition of complex structures and sites. Complete geometry of exposed surface is remotely captured in minutes in the form of dense, accurate "3D point clouds", ready for immediate use. This technique is used for architecture, virtual reality, heritage preservation and some other engineering and civil applications. Laser scanning technology offers many advantages over traditional surveying and photogrammetric methods: better quality results, improved safety during data capture, no interference with construction and operations activities, no time consuming, simplicity and easiness in learning. Furthermore in many cases, it can provide significant cost saving in both capturing surface geometry and in generating CAD models or otherwise using the gathered data.
We applied the laser scanner *Callidus Precision System* to digitise the shape of the three-dimensional small temple inside the Mole Vanvitelliana in Ancona to build a 3D model. It is a complicated task, made harder by the unusually large size of the data sets. We processed the data by several TIN methods to obtain CAD meshes and realize an efficient 3D rendered virtual object close to the reality.

1 CLOSE-RANGE LASER-SCANNER TECHNOLOGY

For more than three decades the measurements of distances by means of laser have been operational in everyday surveying. Only recently the advancements in computer technology enabled the automatic collection and processing of large volumes of laser range data. There are a lot of such systems on the market and they differ from each other (Greco, 2000). The choice depends on the application. The basis of this technology is a scanning laser range finder: the distance from sensor to arbitrary points on the object surface is calculated from the pulse travel time.
Some laser scanners measure distances with the flight time and some others use a phase-difference method. By computing the angles we can only obtain the coordinates of the point in the space.
According to this method, the continuous laser is based on the contrary on the emission of a bundle. This bundle is divided in two wraps: a reference bundle that immediately hits the system for the measurement of the phase; a measure bundle, that hits the object, comes back and arrives to the phase system measurement. By measuring the phase-difference between two wraps it is possible to go back to the distance of the object.
Also, the intensity of the reflected laser pulse is often recorded, providing an indication of the reflection characteristics of the surface. In some systems a fourth dimension, intensity feedback, provides an extra input as to the different materials and colours of an object surface.
The 3D laser scanner is also called an active remote sensing system because no additional personnel are needed to hold a range pole or to place targets for measuring surfaces. Combining a pulsed laser with high speed scanning optics we can get detailed and accurate 3D models of industrial object, works of art, buildings or inaccessible structures (Lemmens, 2001). Once tuning parameters have been set, like horizontal and vertical range and angular steps increment, the creation of the initial point clouds of 3D data is done automatically, thousands of points are scanned every second.
To efficiently use this powerful and innovative technology, it is necessary to plan the survey correctly. A complex object demands the acquisition of the scan data from different positions in the space and the production of several range maps. It can be too large to be acquired in a single step. It can happen also that all the zones are not visible from the same direction of scanning (for instance in case of 3D objects with great elevation). So it is important that the first phase of the scanning process is the plan of all the scans. Furthermore in case of objects with a complex structure, it is necessary to acquire a high number of range maps, partly overlapped, employed for the meshes generation. It is, moreover, advisable to add to these range maps other range maps, in order to acquire particular or small articulated parts of the object. Take into account that the several range maps will have then to be connected in order to reconstruct the total shape. Such a connection has to be carried out manually. It is advisable, to scan together, at least, three flat surfaces, according to the aligning procedure of several software, used as references in the orientation.
3D laser scanning projects enable us to obtain a fine resolution for better modelling. In fact in order to create complete, accurate models and drawings, it is often important to capture precise edges of structures, piping flanges, etc. In addition, to achieve high accuracy results registering multiple scans together, it is necessary to determine accurate positions of at least three scan "targets" within each scan scene. These situations require a high-resolution scanner that acquires features and targets, with a small spot size laser beam.

2 THREE-DIMENSIONAL SURVEY WITH CALLIDUS

The innovative system used in this survey has been the 3-Dimensional Laser Scanner *Callidus* (Fig. 1) (van Spanje, 2001). Thanks to the movement of the sensor (from 30° to 180° for the vertical movement and 360° for the horizontal spin), it allows to measure with extreme accuracy and speed. It is possible to set its field of view, in both horizontal and vertical directions, of 1°, 0.5° and 0.25°. Inside the scanner, two mirrors rapidly and systematically sweep the narrow, pulsing laser beam over the chosen scene. *Callidus* uses a flight time method. To capture complete sites or structures, the instrument can be rotated, tilted, and moved around the site.
The maximum range is 150 meters. Typical measuring accuracy is ± 5 mm below 32 meters. The system's accuracy, even at long range, is determined by many factors: high strength and narrow width of each laser pulse; short laser wavelength; high detection sensitivity; ultra high speed timing circuitry, and small laser beam spot size.
Via the computer it is possible to define the scansion parameters like step angle irons, minimal and maximum range, the regulation of the camera etc., or to visualize the scans in real-time, and to acquire the measurements. A digital camera is placed sideways to the laser sensor. It allows having some images of the survey, for the survey documentation. Every scansion to 360° for million point's heartbeats employs little less than 10 minutes. The files of every scansion are approximately of 2.000 Kb (Levoy, 2001).

Fig. 1: The 3-Dimensional Laser Scanner *Callidus Precision System*

The surveyed object was a small temple inside the Lazzaretto of Ancona, also called Mole Vanvitelliana, built between 1732-1743. This bastioned pentagonal building, made up of a double line of rooms covered with brick cross vaults, was ordered by Papa Clemente XII to Luigi Vanvitelli. In the centre of the courtyard there is a small neo-classical pentagonal temple dedicated to St. Rocco. This building shows, internally, a couple of columns for each pillar; it is considered a visible part of a system for water collection (Fig. 2).
The laser scanning acquired, inside and outside the temple, 8 scans including the buildings facing the courtyard. The number of measured points considered for each scan has been approximately 800.000 at a horizontal and vertical resolution of 0.25° for every scan, at extended horizontal resolution till 2.500.000 points. The final density of the whole model of the surveyed object consisted on many millions of points taken in 45 minutes. The results are graphically displayed like detailed, painted point clouds (Fig.3). In fact for every measured point a direction vector is calculated; it is the result of the average of the normal of the triangle to the bordering measuring points. This direction vector is displayed as point colour in the presentation of point clouds and allows a visual differentiation of the represented surfaces (points of the same direction have the same colour). It can be viewed from any perspective. Every point has an accurate 3D position. The point clouds are an immediately rich data set, already a starting point for many activities. It can be directly used for 3D visualization, point-to-point measurements, or stored for subsequent use. In fact, using the "best fit" software, the clouds can be converted, partially or wholly, into 3D models, 2D drawings, contours, profiles, etc., and used with CAD and rendering applications.

Fig. 2 : The neo-classical temple inside the Mole Vanvitelliana in Ancona

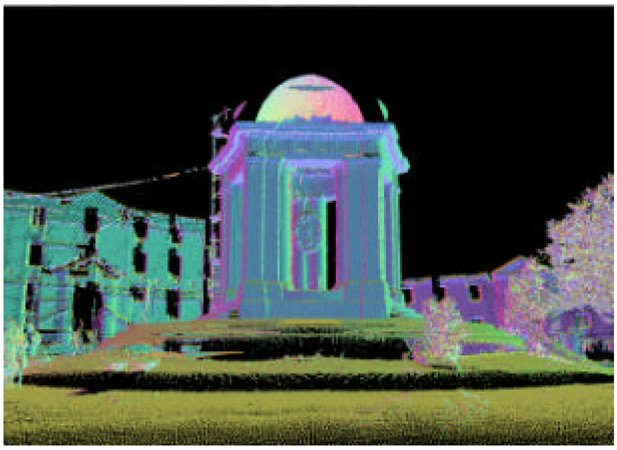

Fig. 3: The point clouds of the laser scanning survey

3 A SERIES OF TOOLS FOR PROCESSING POINT CLOUDS

After the acquisition we have a large size of data sets, which must be processed to model the 3D object surface. First of all, to convert the point cloud into 3D CAD models, we need a powerful PC and an advanced CAD modelling with algorithms of best fitting. A very important thing is how to deal with the large point files. There are few CAD programs that can handle points but most of them cannot properly deal with such information. In fact it is necessary to use appropriate procedures to clean, edit, create meshes and align them.

Such laser scanners use a combined software to merge every scan in a whole 3d model. The peculiarity of the software *3D Extractor* of the *Callidus* System is the possibility to join the scans in a unique reference system. The first procedure to carry out is the loading, in succession, of the single scans until the total composition of the object model in a unique system of reference that has origin in the centre of the laser instrument. The program requires the knowledge of three plans, not parallel (possibly orthogonal), and one of them must be horizontal. The accuracy of such aligning procedure has been estimated from a minimum of 2mm/m, joining 2 or 3 scans, to a maximum of 2.5 cm/m using the total number of scans (in this case 8 scans).

Furthermore it is possible to increase the number of points of the imported cloud. They can be included by refinement of selected areas. When measured values are imported in a reduced way, it is possible to reload the measured points that are left out in those areas where the point density needs to be increased (Fig. 4).

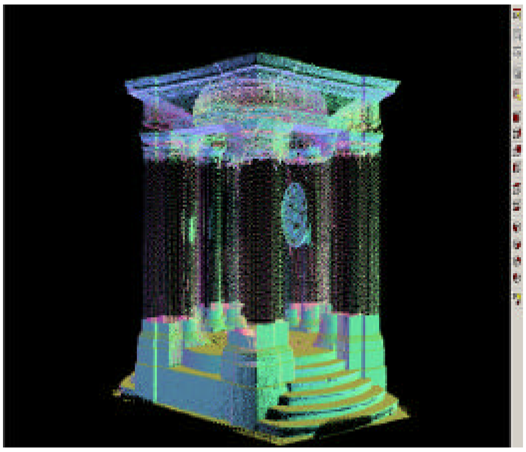

Fig. 4: The refinement of selected areas

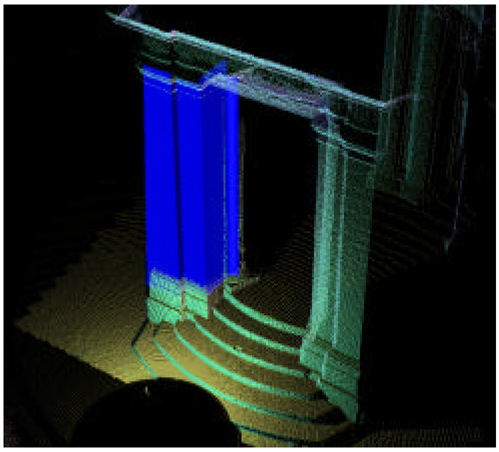

Fig. 5: The best fit of regular parts by simple geometrical shapes

After merging the multiple scans, the software allows to measure coordinate and distances, to export vertical and slanted horizontal sections, to create surfaces and meshes and to export the data in the DXF or ASCII formats, for further processing with other software. The possibility for interfacing with CAD and GRAPHICS systems is of great importance.

To reconstruct the 3D object surface it is possible to use a manual process, which converts the set of data into a restricted set of shapes. Depending on the application, a considerable amount of manual work is needed for this task in order to convert the data into suitable 3D CAD models.

In particular by means of the software *3D Extractor*, it is possible to fit homogenous and regular parts of point clouds selecting some simple geometrical shapes (plane, cylindrical, spherical and conical). This procedure is very time-consuming and does not always supply appreciable precisions and results (Fig. 5).

In order to obtain a good result we tested many other software (*Rapidform2000 – Poliworks InnovMetric – Spider AliasWavefront – VCG's 3D scanning tools by ISTI-CNR of Pisa – Paraform Points2Polys*) for the management of point clouds deriving from the single scans. Some of these realize a mesh from a single scan and then merge every grid in a global surface; some others immediately obtain, the 3D modelling from full point clouds.
These software use the data in ASCII format and allow to reduce it by several filters. The noise filter automatically removes some incorrectly measured points. It can be used repeatedly and the detected vertices as noise points are removed in any iteration. The operator must be careful because correct data also may be removed. The redundancy filter automatically reduces the number of the vertices when too many of these are overlapped.
These new and innovative polygon-based processes provide a point cloud triangulation, multiple scans view aligning, polygon merging, dimension measuring and polygon modelling for a wide variety of applications.
We present the tasks performed by these software and the good results obtained.

4 GRIDDED SURFACES USING TIN

We present now a panorama of several software for laser data processing to obtain a regular mesh generation. When it is not possible to decompose the 3D objects into simple geometric shapes, it is necessary to structure the point set by applying TIN-polygons. This happens when the 3D objects to survey are, for example, statues or buildings, for the generation of a TIN model, for the visualization and the rendering purposes.
There are several Triangular Irregular Network methods available and they can be differently combined (Besl, 1992).
The need to construct a globally optimal triangulation suggests working with the *d*-dimensional version of the *Delaunay* triangulation (the dual straight-line of the *Voronoi* tessellation). An appropriate triangulation is generally chosen to satisfy some optimality criterion, which guarantees, first of all, a unique triangulation, possibly without elongated triangles. The *Delaunay* triangulation can be constructed using an appropriate *"circle criterion"* in 2D dimension or the *"spherical circumscribed circle criterion"* in 3D dimension (Crippa et al, 1998).
This method can be adapted to generate grids for realistic problems in which the distribution of the points does not always constitute a convex dominion (criterion of *Delaunay* constraints). A triangulation satisfying such criterion is that where the circle circumscribing every triangle does not contain visible nodes of the grid.
The processing of the measuring points is realized in different cyclical steps to create the object surface. Some software realize this task both using 2D or 3D TIN methods, others using directly 3D TIN ones.
These software work directly with the raw 3D point clouds data generated from laser scanners and convert it to polygon meshes, in a one-to-one correspondence between point clouds and polygon mesh. It is possible to import multiple point clouds and to combine them to create a single point cloud, then to triangulate the cloud to form a single polygon mesh. The resulting polygon meshes may be edited and/or used to generate surfaces or to be imported directly into other applications.
The 2D triangulation method projects vertices in a three-dimensional space onto two-dimensional plane and then, applies *Delaunay* triangulation process to project vertices. Thus, for proper triangulation, all the vertices must be projected onto XY plane without overlap. To obtain good results by 2D triangulation it is necessary to grid the single scan from different points of view and then to merge each in a complete grid model (Fig. 6).

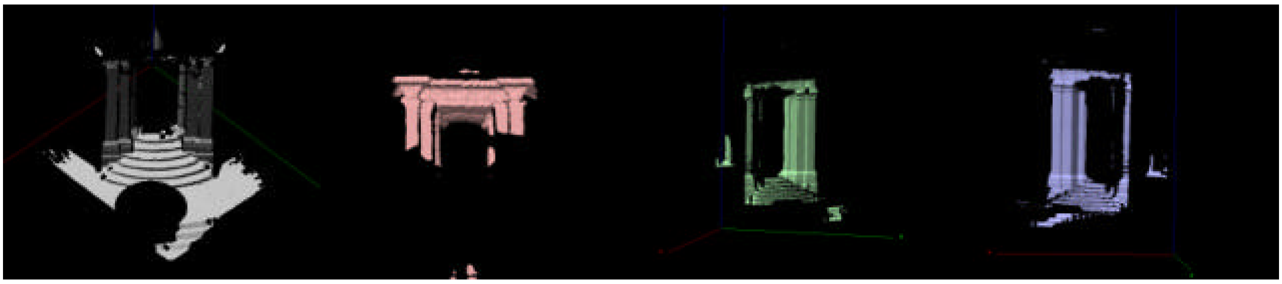

Fig. 6: The scan data are interpolated on a 2D plane grid from different angles

On the contrary, by using 3D triangulation method, it is possible to convert a full 3D point cloud set into a polygonal model.
Possible limitation of the created surfaces to the real existing ones depends on the reduction of the number of surface pieces resulted from the intersection of near surfaces. It is possible to classify these surface pieces as elements with real reference in the measured object or as definitely non-real (virtual) and to reduce them by joining boundary surface pieces or by definitely removing virtual surface pieces.
Furthermore it is often advisable to decrease the density of a mesh to make it more manageable, reducing a percentage of the original number of polygons or of a specific number of polygons and maintaining the shape of the mesh within a certain tolerance. Any level of reduction can be obtained with these approaches, under the condition that a sufficiently coarse approximation threshold is set. Lower values give less reduction but more fidelity to the original (Cignoni et al, 1998).
The next images show a comparison of the TIN methods applied by different software (Fig. 7, Fig. 8, Fig. 9).

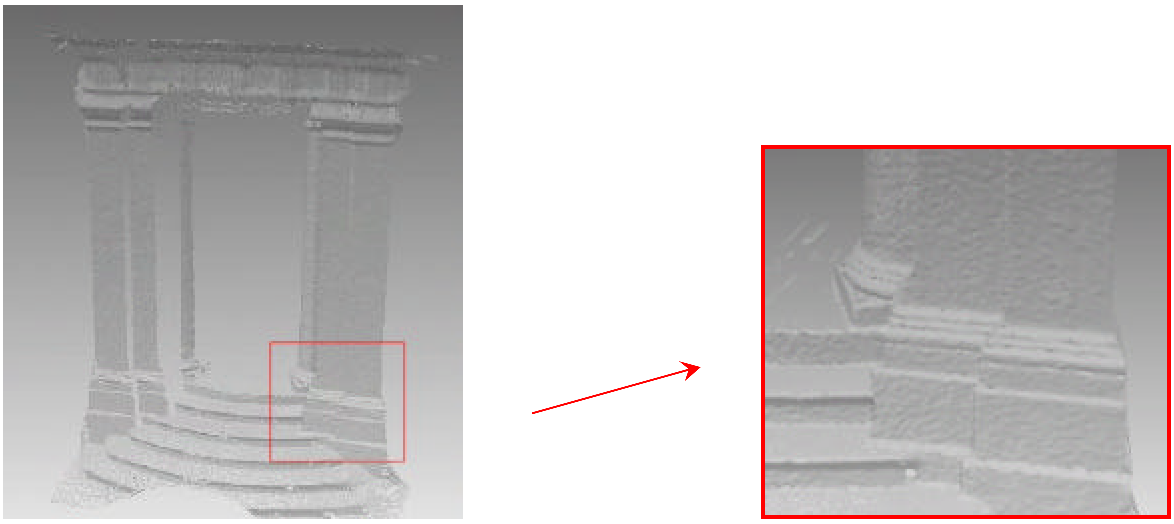

Fig. 7: Result obtained by TIN method (*software Rapidform2000*)

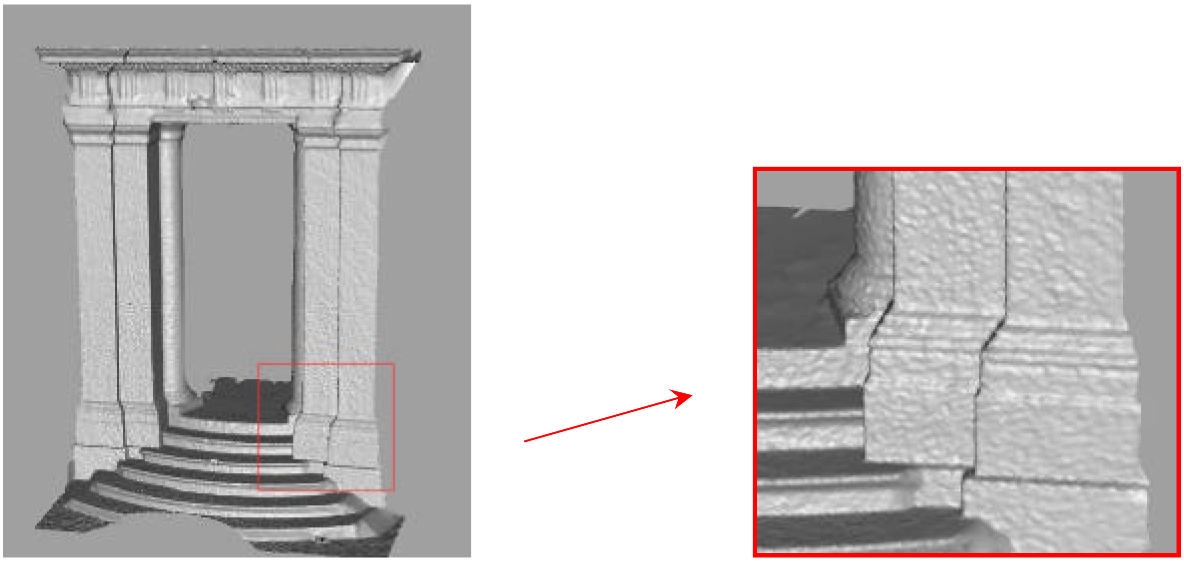

Fig. 8: Result obtained by TIN method (*software Paraform Points2Polys)*

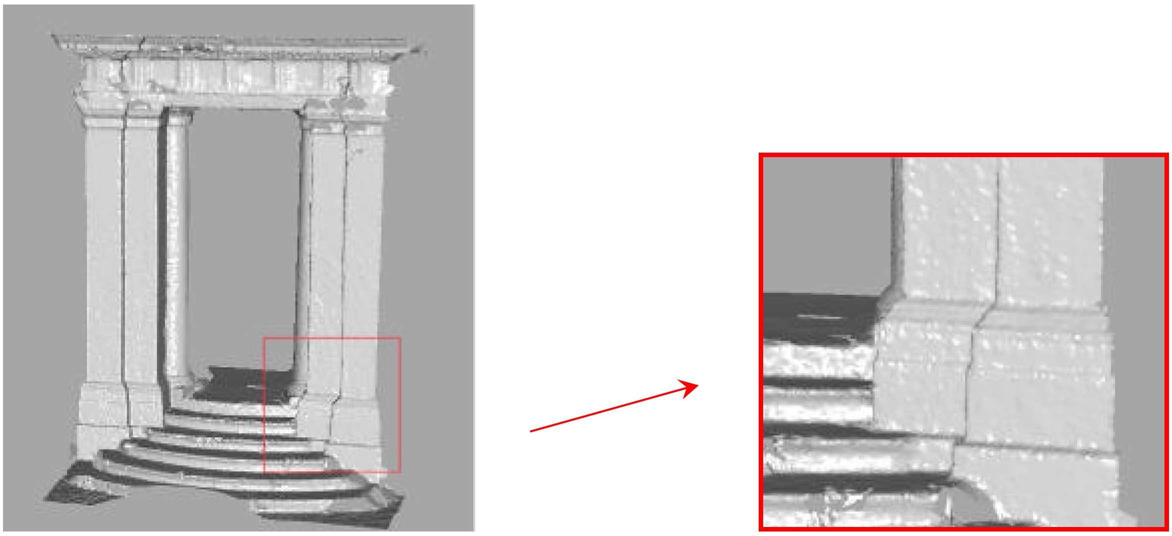

Fig. 9: Result obtained by TIN method (*software Spider Alias Wavefront*)

5 THE 3D POLYGON MODEL REPRESENTATION

After the interpolation, the next step is the alignment phase that consists on the alignment of the meshes into the same coordinate system and to prepare the data for the merging phase.
It is possible to merge meshes that have been aligned into one united mesh, by more than two meshes at a time. Registration is the process that aligns two or more meshes on the basis of the coordinate of a fixed mesh. It calculates the exact position of each mesh by utilizing the common geometries between the two meshes. The user can specify common geometric features, also called corresponding points. On the contrary, the global command exactly matches the position of all the selected meshes at the same time using the overlapped region, which is automatically found.
During the merging process, overlapped regions between meshes are effectively removed and neighbouring boundaries are stitched together with newly added faces. The result and the accuracy of the meshes are still maintained.
After merging, there can also be some holes or crossing faces. Sometimes the result of two merged meshes is not good enough, the average distance between overlapped regions of the merged meshes can be relatively far. This problem can include measurement errors of the three-dimensional measurement equipment. In some cases, it can be due to decreased face resolution.
The next image (Fig. 10) shows the single meshes used for the merging procedure and the alignment results using, for example, *Poliworks Modeler Process* (Roberge, 2001).

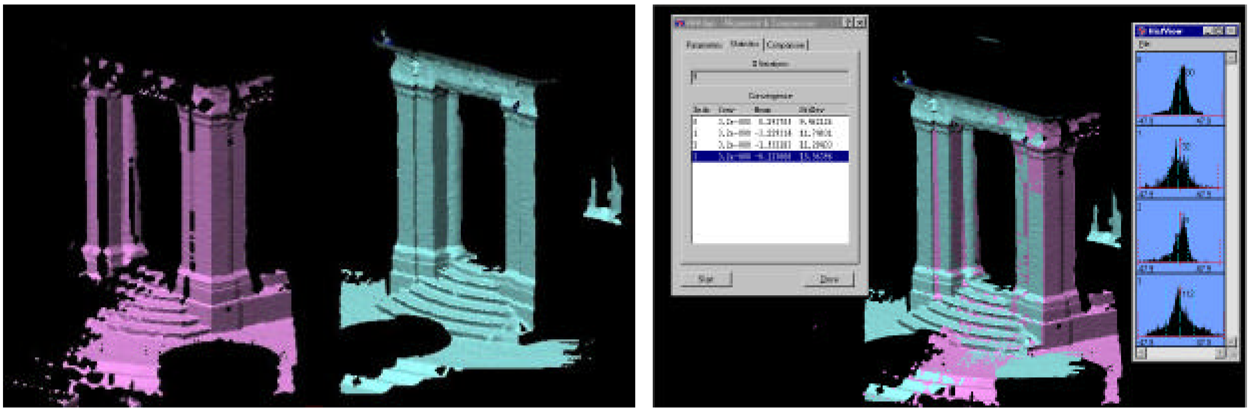

Fig. 10: The split meshes and the alignment results using *Poliworks Modeler Process*.

The next picture shows the merging of the scan data to generate a polygonal model (Fig. 11). Some smoothing and reduction parameters have been used to eliminate the noise and to reduce the file size. The holes have been filled with automatic editing tools. The polygonal model can be exported in .stl or .obj format among others or .vrml. Also the cross-section generation and the cross-section polylines are exportable in .dxf or .iges file format.

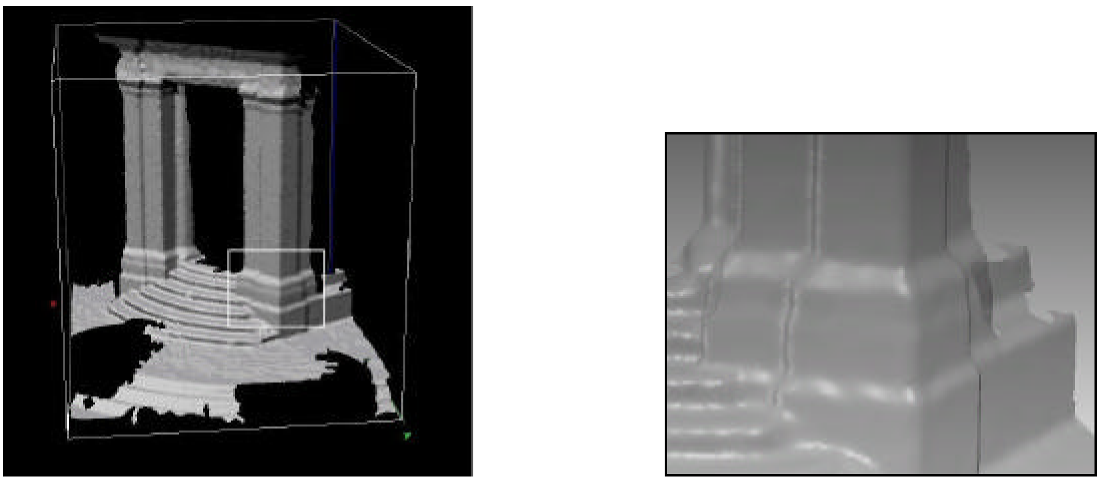

Fig. 11: The merging of the scan data to generate a polygonal model using *Poliworks Modeler Process*

After the creation and manipulation of a polygon mesh, it is possible to evaluate its deviation from the original point cloud. The program displays a colour map on the mesh showing its deviation from the cloud. A colour bar on the right side of the view window displays what deviation the colours represent (Fig. 12).
Finally the 3D modelling of the whole object, obtained with other software, is shown (Fig. 13, 14).

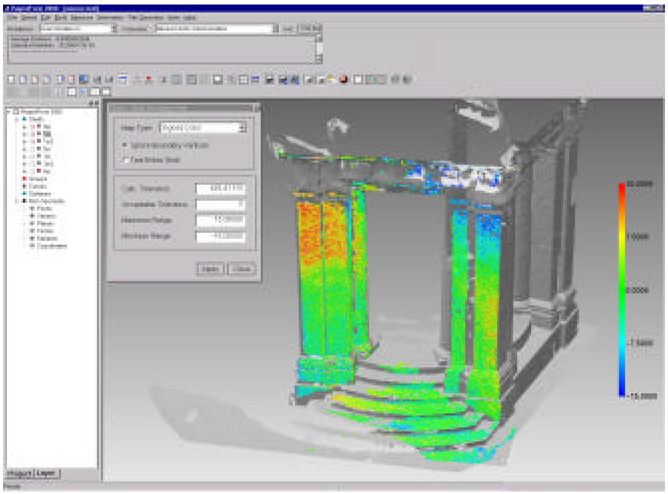

Fig. 12: The deviation between the cloud and the mesh obtained by a merged meshes by *Rapidform2000*

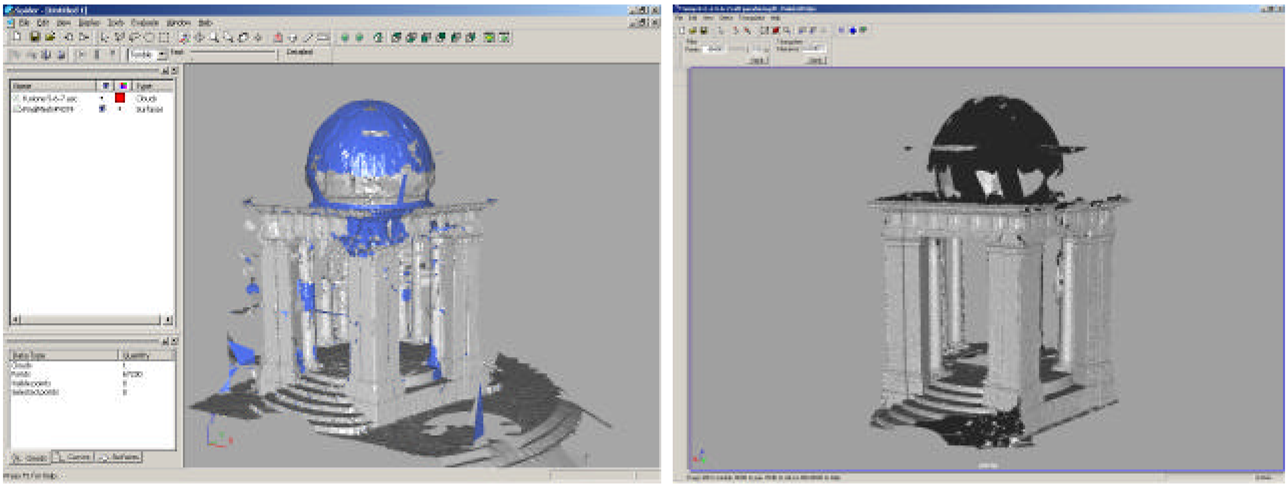

Fig. 13: The 3D modelling of the same object by *Spider Alias Wavefront* and *Paraform Points2Polys*

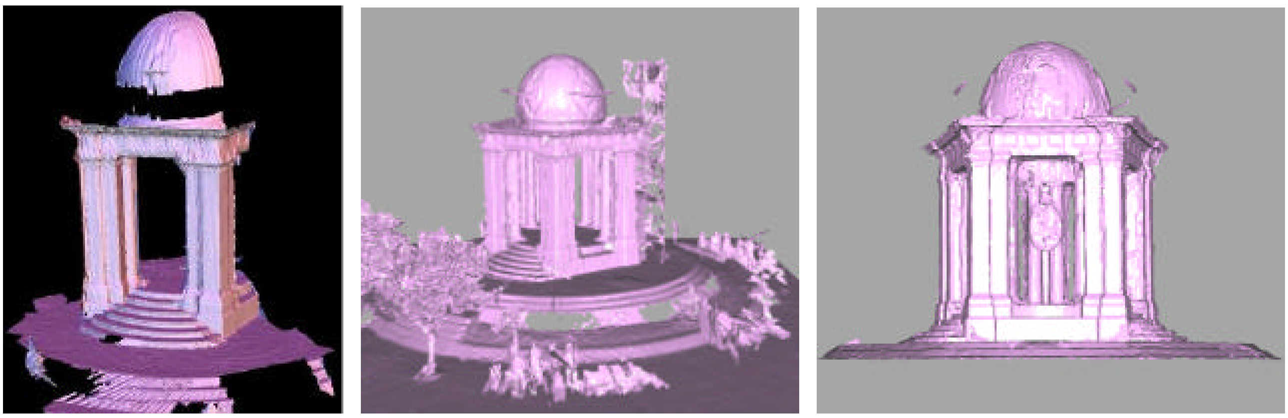

Fig. 14: Other polygon models generated by suitable software of *CNR of Pisa* (Italy)

6 CONCLUSIONS AND REMARKS

We described the several tasks for the generation of a suitable complex 3D object from 3D scanning data. In particular, we presented a series of tools to process range maps, to align and merge the TIN meshes: a panorama of different solutions (applying several software) and some methods to obtain good results for the better visualization of the object, close to the reality.

The problems were even harder by the unusual large size of the data sets, by the non-homogenous reference system and by a not good acquisition planning.
Another problem regards the quality of the laser scanner survey. It depends on many accidental factors influencing the laser beam propagation. Such factors are not easy to foretell. Some experience is needed. In practice the same object from different points of view can be measured in different atmospheric conditions, in order to compare the results. Furthermore the laser beam hitting the surface that is normally not smooth, is reflected in various ways according to the local superficial roughness (Fig. 15). The type of material hit by the pulse determines the intensity of the returning signal. This sometimes produces a degradation of the quality of the range data and it may even happen that no signal at all will return. It is called white noise.

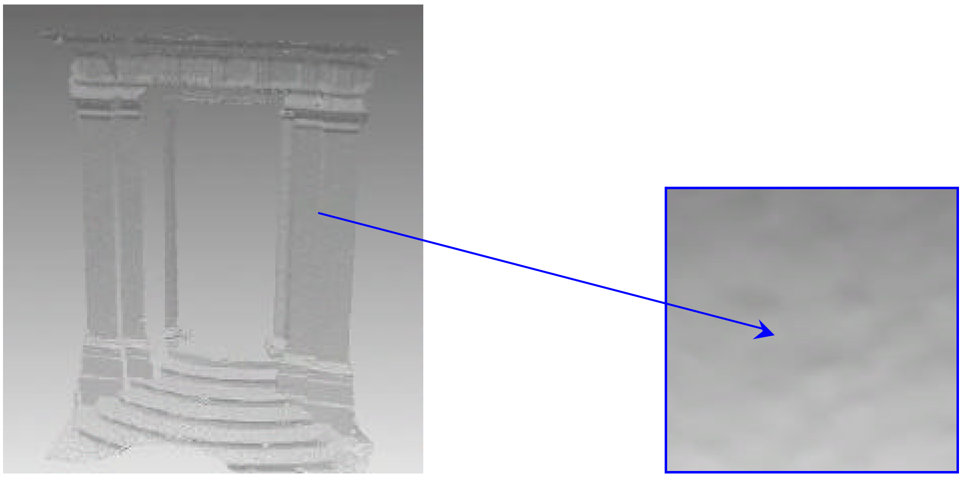

Fig. 15: An example of white noise

From these and many other issues it can be easily understood that the measurements will be affected by an error that does not depend only on the surveying instruments and its accuracy but also on the planning and technology. In conclusion, it is necessary to establish how reliable the instruments in relation to the type of object. In other words, we have to be able to produce a good survey, some practice is needed in order to estimate the quality and reliability of the gathered data.

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REFERENCES

P. J. Besl, N. D. McKay, 1992. A method for registration of 3-D shapes. IEEE Transactions on Pattern Analysis and Machine Intelligence, vol 14, n. 2, pp. 239-256.

P. Cignoni, C. Rocchini, R. Scopigno, 1998. Metro: measuring error on simplified surfaces. http://vcg.iei.pi.cnr.it/metro.html

B. Crippa, E. S. Malinverni, G. Tucci, 1998. Complex Surface Representation. International Archives of Photogrammetry and Remote Sensing, vol. XXXII, part. 6W4, pp. 125-133.

J. Greco, 2000. The Cyrax 3D laser scanning system. http://www.cadenceweb.com/features/mcad_future/greco.html.

Inus Technology, Inc. Rapidform2000. Tutorial and Reference Manual. http://www.rapidform.com

M. Levoy, et al., 2000. The digital Michelangelo project: 3D scanning of large statues. In Proceedings of Siggraph 2000. http://graphics.Stanford.edu/projects/mich.

M. J. P. M. Lemmens, F. A. van de Heuvel, 2001. 3D Close-range Laser Mapping Systems. GIM International, January, pp 30-33.

E. Roberge, 2001. Poliworks Modeler Process. http://www.innovmetric.com

C. Rocchini., P. Cignoni, C. Montani, P. Pingi, R. Scopigno, 2001. A suite of tools for the management of the 3D scanned data. In Proceedings of Workshop Italy-Canada “3D Digital Imaging and Modelling Applications of: Heritage, Industry, Medicine & Land.”

Alias|Wavefront, 1999-2000. Spider Mesh Creating Software http://aw.aliaswavefront.com/special/spider/index1.html

Paraform http://www.paraform.com/

W. van Spanje, 2001. Product Survey on Laserscanners....An Overview. GIM International, January, pp. 49-51.