A NEW SOFTWARE FOR THE AUTOMATIC REGISTRATION OF 3D DIGITAL MODELS ACQUIRED USING LASER SCANNER DEVICES

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KEY WORDS: LIDAR, Registration, Close Range, Architecture, Software

ABSTRACT:

Laser scanner devices that allow the reconstruction of complete and dense 3D digital models, have recently been introduced into archaeological and architectural surveying methods. These 3D models are produced by means of the registration of many simple models that have been directly acquired with laser devices.
This problem can be solved using the original, fully automatic software that has been implemented by the authors. The software locates pre-signalised points using reflecting markers and recognizes common points from two adjacent scans. The obtained points are used for the estimation of the registration parameters.
The software also performs error filtering from the acquired raw data using robust statistical tools and, finally, the exportation of the obtained digital model using widespread file formats, e.g. DXF and VRML.
This paper describes the implemented algorithms and the automation that can be obtained with the software LSR (Laser Scanner Registration) that has been developed by Politecnico di Torino research group.
This software package, which is able to create an accurate 3D model in a fully automatic way, is described in this paper. The procedures are demonstrated by means of a practical example: the creation of a 3D digital model of the roman bridge of Pont Saint Martin, in the Aosta Valley (Italy).

1. INTRODUCTION

Terrestrial laser scanner devices today represent one of the most widely investigated instruments in the field of architectural and archaeological surveying applications.
The main topics of the research activities can be summarized as: quality of the primary data, registration and geo-referencing of multiple scans, integration with other survey techniques (e.g. photogrammetry).
In order to allow a correct and wide diffusion of this instruments, all these problems must be solved considering the particular fields of application that require cheap and easy-to-manage solutions.
The quality data of the laser scanner devices can be split into two: metric accuracy and practical usability of the data. As far as metric quality is concerned, laser scanner data always confirm the standard deviation declared by the instruments; in the past many tests confirmed this fact. The quality related to the practical usability of the data can be defined as the possibility of the acquired points of correctly describing the surveyed object and allowing easy management by the final user (e.g. profile production). The complete description of the shape is strictly related to the density of the acquired points: only high densities allow the identification of the break-lines but, on the other hand, high densities produce enormous amounts of data and, as a consequence, a great deal of problems in the management of the data themselves.
The registration and geo-referencing of multiple scans has been the most investigated topic so far. A great deal of interactive solutions have been proposed by different research groups and possible automation of the procedures has been investigated following the procrustes analysis approach or using high reflecting marks.
Some simple integrations of laser scanning with photogrammetry (e.g. true orthophoto and 3D realistic modelling) have been tested in recent years, but further integrations should be performed to achieve new ways of representing architectural objects (e.g. direct and automatic orientation of images, automatic feature extraction, etc.).
A new approach for the registration of multiple scans and for the improvement of the quality of laser scanner data, based on the use of reflecting targets, is here presented.

2. DATA REGISTRATION

A laser scanner can be considered as a motorised total station that is able to acquire thousands of points in a few seconds. When the laser scanner operates, the surveyed points are referenced to an internal coordinate system (see fig. 1).

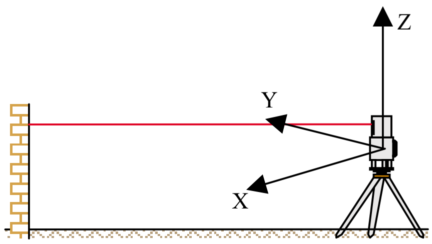


Figure 1. Internal reference system of a laser scanner

When the object has a complex shape or when a single scan cannot record the entire object, a series of scans must be performed. In this case each scan has is own reference system (see fig. 2): the reconstruction of the 3D model of the surveyed object requires the registration of the scans in a single local reference system.
This phase can be performed in an interactive environment through the identification of the homologous points (e.g. corners) in adjacent and overlapping scans. Once the points (at least three) are collected, a simple 6 parameter transformation

can be estimated and all the points of a scan can be changed into the coordinate system of a scan that has been assumed as the reference system.
If this simple approach is followed, all the scans that describe an object can be referenced to a single coordinate system (e.g. the first scan coordinate system or an external system defined by at least three points).

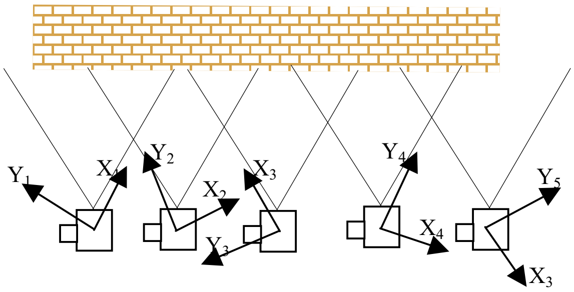


Figure 2. Multi scan for large objects

From a photogrammetric point of view, this procedure is the same as the one that is used in independent model triangulation; therefore the same problems arise. Small overlaps between adjacent scans lead to systematic errors during the junction of adjacent scans; these errors can be overcome with a final compensation using at least one or two points for each scan surveyed by means of a total station in a terrestrial reference system.
This procedure requires a large amount of human intervention to collect homologous tie points inside the overlapping portions of adjacent scans.

2.1 Automatic tie point collection
The collection of tie points and the search of the homologous in adjacent scans can be performed automatically using reflecting targets.
Laser scanner devices record the X, Y, Z point coordinates and the average reflectivity of the impact area of the laser beam. Buildings are usually made of poor reflective material (e.g. stones, clay). If some reflective targets are superimposed onto the object, they can easily be found (see fig. 3) simply by selecting, from all the acquired points, those which have a higher reflectivity than a prefixed value (e.g. the higher reflectivity value of the material of the object).

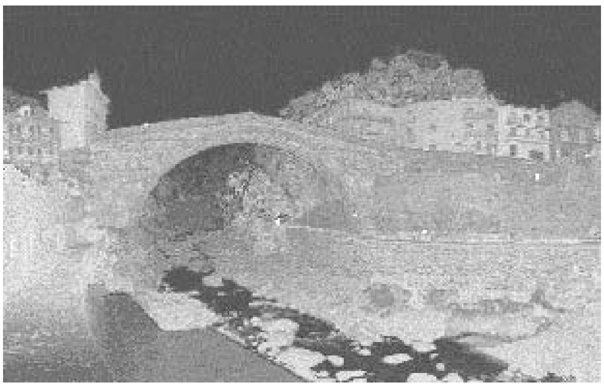


Figure 3. Digital representation of the recorded reflectivity values using the laser scanner

The reflecting target must be placed on the object in such a way that at least three targets can be found in the overlapping portion of two adjacent scans. The size of the target must be large enough to allow the laser scanner to record it.
If the usually adopted beam divergence is considered, square target sizes of 2 cm x 2 cm can satisfy almost the whole application of architectural object recording. The same targets can be used for a total station survey to obtain the necessary information for the positioning of the scans in an external defined reference system.

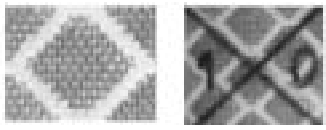
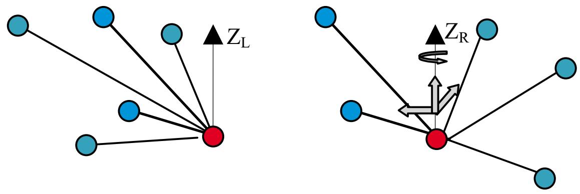


Figure 4. Reflecting targets

The reflecting targets must be placed far from other high reflective objects in order to avoid errors in this phase.

2.2 Homologous tie point correlation
Let us consider two adjacent overlapping scans. Some reflecting targets (at least three) have been placed in the overlapping portion and recorded by the laser scanner. All these targets can easily be automatically found (see previous paragraph)and the coordinates can be recorded.
The purpose of this procedure is to connect each point of the right scan to the homologous point of the left scan; the reference system of the latter scan is fixed and only the point recorded in the right scan can rotate and translate in space.
It can be assumed that the Z axis of the two scans are vertical: actually all laser scanner devices are placed on the ground on top of topographic tripods and stage plates.
This hypothesis simplifies the search for homologous points: if one starts with the two vertical Z axis search for the right set of points can rotate around their Z axis and translate in space but they cannot rotate around their X and Y axis.



Left set of points Right set of points

Figure 5. Reflecting targets found in the adjacent scans

This problem is solved in two subsequent steps. Using the points of the left set, the procedure calculates two spherical coordinates (range and elevation) of the points considering each time one of the points has the origin O_{Si}: in the case of figure 5, six series of spherical coordinates are determined.
Using the points of the right set and one of these as the origin O_R, the same two spherical coordinates of the remaining points are then determined. These coordinates are compared to all those of the previously computed six series and the one which has the maximum number of equal coordinates (both range and corresponding elevation angle is selected). Point O_R is considered to be the homologous of the origin O_{Si} of the selected spherical coordinate set. This procedure is iterated for each point of the right set of points. The equality of the coordinates is judged according to the range and angles tolerances that are typical for the laser scanner.
If one of the comparisons gives no equality for at least one point, it means that the point O_R is not present in the left set of points.
Once the homologous points have been selected, the procedure verifies the obtained results by comparing the differences between the angular spherical coordinates (elevation and

horizontal angles) of the homologous points, considering one of them as the origin both on left and right sets of points.
This verification is performed, by iteration, using all the selected homologous points as the origins. Only the homologous points that pass all the tests are accepted as precise homologous points.

2.3 Registration parameter estimation
The estimation of the six parameters of a 3D coordinate transformation is performed, using the homologous points accepted by the last step of the procedure described in the previous paragraph. All the points of the right scan can then be transferred into the reference system of the left scan using the well known model
(1)

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \mathbf{R} \cdot \begin{pmatrix} x \\ y \\ z \end{pmatrix} + \begin{pmatrix} X_0 \\ Y_0 \\ Z_0 \end{pmatrix}$$

where X, Y, Z are the coordinates of the left scan, x, y, z the coordinates of the point in the right scan and **R** is the rotation matrix.

3. DATA QUALITY IMPROVEMENT

The data acquired by laser scanner devices always has noises which are smaller than the tolerance of the used instruments. This problem is evident if one tries to create a 3D photographic model of the object (see figure 6).

Figure 6. Image projection on original laser scanner data

The noisy data do not allow a correct interpretation of the details. The noises are caused by the beam divergence: the measured distance is the average of the distances of the points of the object contained in the foot print of the laser beam.

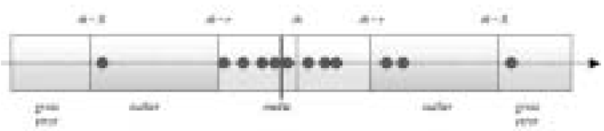


Figure 7. Data noise reduction

In order to resolve this problem, a procedure based on robust estimation has been studied and implemented.
The original data are subdivided into 3D meshes whose sizes can be two or three times those of the adopted scanning rate. Each mesh contains a set of measured points. The median ($\breve{m}$) of the distances is estimated and the deviations of the single values are computed from their median.
The distances which have smaller differences than the laser scanner accuracy are used for the estimation of the real distance using the mean; the other points are rejected.
Figure 8 shows the practical effect of the removal of noise performed with the described procedure.
This technique also allows the removal of any points which are not on the object of interest (see fig. 18).

Figure 8. Image projection on filtered laser scanner data

4. LSR SOFTWARE

In order to practically apply the previously described procedures, a specific software, named LSR, has been developed using Visual Basic language.

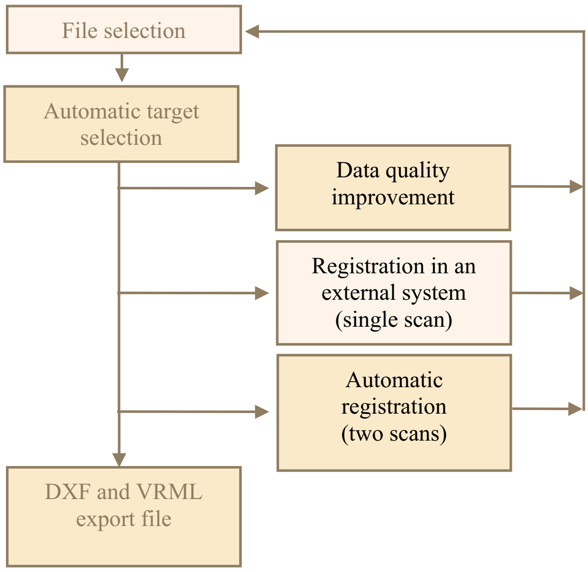


Figure 9. LSR procedures

The software runs both the data registration and the data quality improvement procedures and produce a final correct 3D model.
The LRS program can perform three basic procedures: filtering of the original data (automatic procedure) and registration of the

selected scan in an external reference system (interactive procedure), registration of two adjacent scans (automatic procedure).

4.1 Starting

The operator introduces some information on the used laser scanner (e.g. measurement accuracies, beam divergence), the size of the reflecting targets and the value of their minimum reflectivity. This value can be based on the reflectivity image (see fig. 3): in standard conditions it decreases with the distance. The minimum reflectivity should then be tested on the furthest targets. This value can sometimes also characterize also other object (e.g. vegetation, road signs): in these cases, the operator has to previously erase the undesired portion of the scan or operate in different portions of the scan with different threshold values.

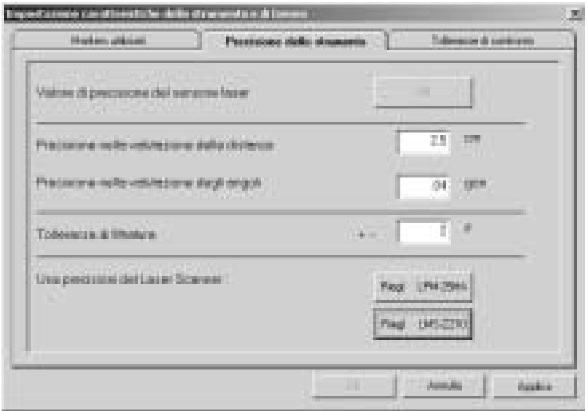


Figure 10. General information input window

4.2 Scan selection

The operator selects one or two scans that must be registered. The program operates in ASCII files; as all laser scanner devices usually export the data in this format, the LRS software can operate independently from the used instrument.
A preview of the selected files is shown and the operator can indicate the data format (e.g. x-y-z-reflectivity or range-horizontal angle-elevation angle-reflectivity).

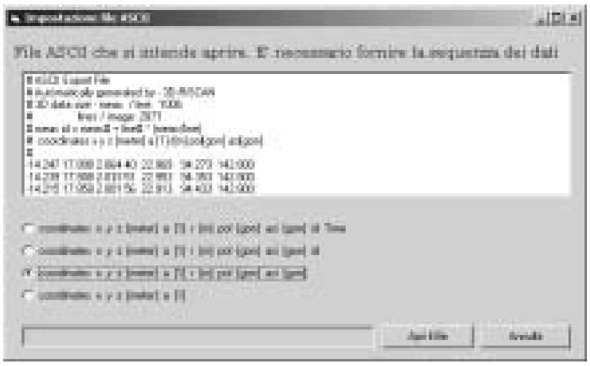


Figure 11. Data format input window

4.3 Target selection

The automatic selection of the reflecting marks runs on the selected scans.
First of all, the procedure extracts all the points that have a reflectivity value higher than the threshold fixed at the beginning; in a second step, these points are clustered in order to group all the pointsthat describe the same reflecting marker.
This clustering is performed considering the beam divergence and the diffraction of the high reflective points (e.g. a square target with a 2 cm side is identified by points grouped in a circle with a diameter of 4 cm).
The coordinates of the target, computed as the mean of the coordinates of the clustered points, are recorded in a separate file which is joined to the scan file for all the subsequent elaborations.

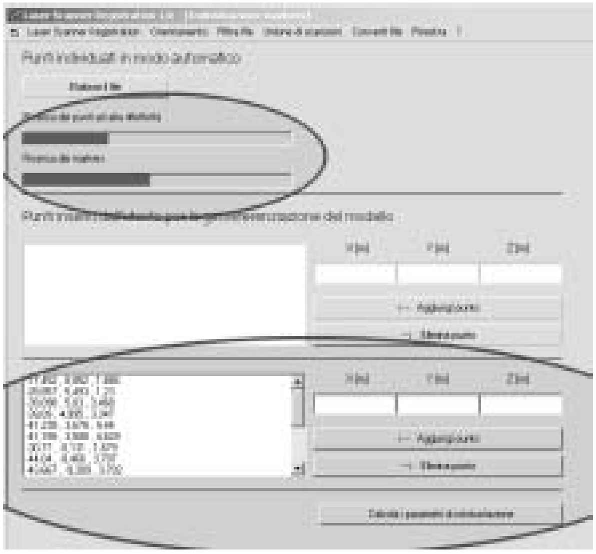


Figure 12. Automatic target selection

Obviously, this step can only run using the original scans. The previously described filtering data noise reduction (see par.3) makes it possible to loose the correct position of the reflecting targets.

4.4 Data noise reduction

This procedure runs for each single scan. The operator has to choose the mesh dimensions indicating the angular steps in spherical coordinates. The size of the mesh must be at least two or three times larger than the acquisition scanning rate in order to provide a consistent number of points to the described algorithm.

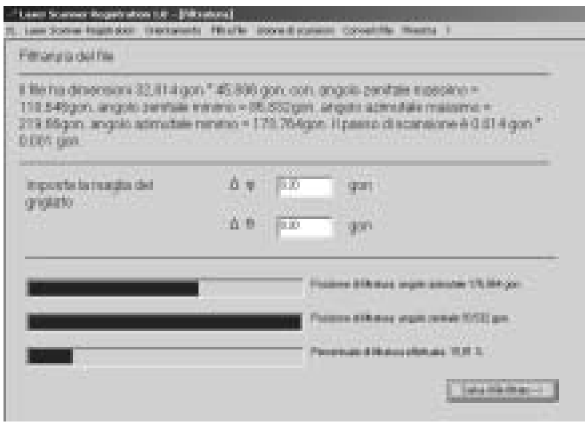


Figure 13. Data noise reduction window

4.5 Single scan registration in an external system

This step simply allows the registration of a single scan in a reference system defined by at least three points of known coordinates. The known points are selected by the operator on the scan and the transformation parameters are estimated; than all the measured points are transformed in the external reference system using the equation (1).

4.6 Automatic registration

Using two overlapping scans, the LSR software performs the automatic registration following the procedure described in paragraphs 2.2 and 2.3.
The operator can evaluate the success of the registration using an analysis of the statistics of the estimated transformation parameters and the residuals on the used reflecting targets. A first practical evaluation of the procedure can be performed by looking at the graphical result of the registration.

Figure 14. Registration results

A complete test of the LRS software is described in the next paragraphs.

5. THE 3D MODEL OF A ROMAN BRIDGE

The object of the survey is to obtain a 3D model of the *Pont Saint Martin* Roman bridge located in the Aosta Valley –Italy (see fig. 15).

Figure 15. The Pont Saint Martin Roman bridge

Before the laser scanner acquisition, 5 reflecting targets were placed on the two sides of the bridge (see fig. 3). The Riegl LMS-Z210 laser scanner has been used. This instrument, recently acquired by The Politecnico di Torino, has a measuring range of 350 m and a measurement accuracy of ± 25 mm. An angle step-width range was selected from 0.080 gon to 0.4 gon while an angle readout accuracy of 0.04 gon for the line scan mode and 0.02 gon for the frame scan were selected.
Figure 16 shows the location of the instrument during the acquisition phase. The acquisition distances range from 3 m and 330 m; the measured bridge points therefore have an average step of about 5 cm. The overlap between two adjacent scans is almost of 50 %.
The selected angle step-width is of 0.080 gon for each scan.
All the acquired 3D models have been processed using the LRS software. All the points of the bridge show a reflectivity that is lower than 100 Digital Number (reflectivity range 0-255 DN) and the reflecting targets have a mean reflectivity of about 200., The program found all the reflecting targets recorded by each scan because of the high differences in reflectivity values of the targets.

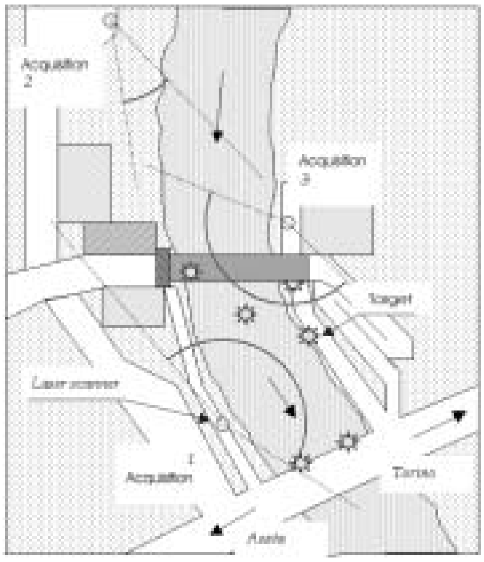
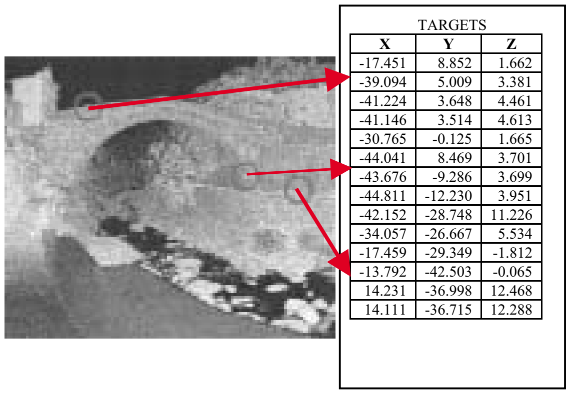


Figure 16. Laser scanner acquisition



TARGETS

X	Y	Z
-17.451	8.852	1.662
-39.094	5.009	3.381
-41.224	3.648	4.461
-41.146	3.514	4.613
-30.765	-0.125	1.665
-44.041	8.469	3.701
-43.676	-9.286	3.699
-44.811	-12.230	3.951
-42.152	-28.748	11.226
-34.057	-26.667	5.534
-17.459	-29.349	-1.812
-13.792	-42.503	-0.065
14.231	-36.998	12.468
14.111	-36.715	12.288

Figure 17. Reflecting target extraction

After the computation of the registration parameters, each scan was filtered in order to remove the acquisition noise. As mentioned in paragraph 3 this procedure also allows the elimination of any acquired points that are not on the object (see fig. 18).

The mesh used for the data noise reduction is of 0.24 gon, which means an average distances between the filtered points of about 15 cm.
The filtered scans were registered using the reference system of acquisition 1 as the local reference system for the 3D model.
Figure 19 shows two adjacent scans in their own reference systems while figure 20 shows the two scans oriented in the reference system of the final 3D model.
Finally, the 3D model was converted into DXF and VRML format (see fig. 21).

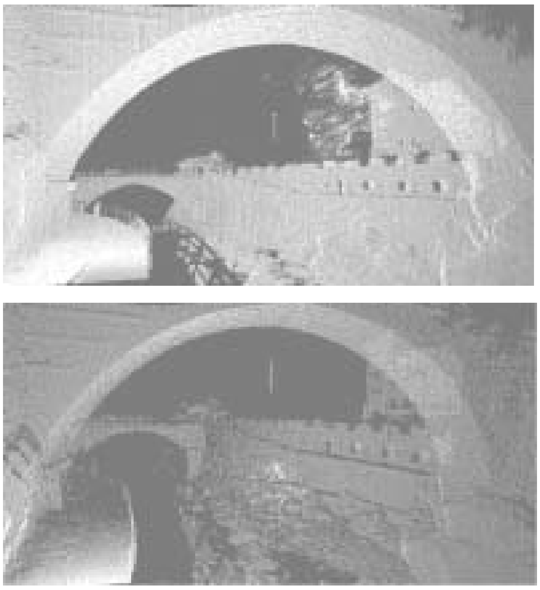


Figure 18. Original and filtered scan

The 3D model is now ready the subsequent elaborations (e.g. true orthophoto production, geometric interpretation,…).
The whole procedure has been performed, using a standard PC, in less than 40 minutes.

Figure 19. Adjacent scans in the acquisition reference systems

Figure 20. Adjacent scans in the 3D model reference system

6. CONCLUSIONS

Laser scanner device producers offer many different types of software for the geometric management of the acquired data. These software packages were developed for mechanical application purposes but they are not able to supply an adequate answer to the particular field of architectural surveying.
While mechanical applications usually have to describe standard surfaces (e.g. spherical, cylindrical), architectural surveying has to manage complex surfaces that cannot be simplified.
The proposed algorithm and its practical application through the LSR package offers the possibility of correctly managing the data acquired using terrestrial laser scanner devices for the surveying of architectural objects.

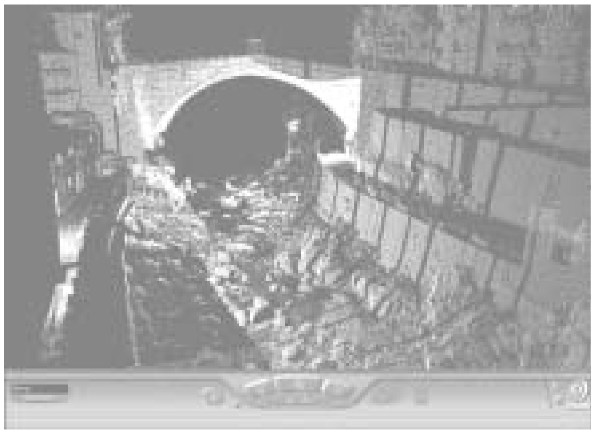


Figure 21. 3D model managed by COSMOS VRML viewer

The software automatically runs some basic procedures but requires direct intervention for some special procedures, allowing maximum flexibility.
The automation level reached by the LSR software allows even unskilled operators to use the acquired data; all the problems that involve specific metric survey knowledge are solved by the software itself.
The 3D model produced by the LSR is not the final product of the survey but represents the correct starting point for vector extraction, 3D image model construction and basic geometric interpretation.

7. REFERENCES

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8. ACKNOWLEDGEMENTS

The research has been financed by Italian Ministry of Education, University and Research (MIUR) project COFIN2000 (Nat. Resp. Prof. Carlo MONTI – Research Group Resp. Prof. Sergio DEQUAL).